FINAL REPORT

DESIGN AND TESTING OF SMALL COMPOSITE SPECIMENS

Avva V. Sharma

Professor of Mechanical Engineering

NSG-1631 1979-81

Prepared for
Langley Research Center
National Aeronautics and Space Administration
Technical Officer: Marvin D. Rhodes

School of Engineering
North Carolina A. & T. State University
Greensboro, North Carolina

December 1981

Date: 7/15/95 Time: 5:58:46PM

Page: 1 Document Name: untitled

DTIC DOES NOT HAVE THIS ITEM

```
-- 1 -  AD NUMBER: D436204
-- 5 -  CORPORATE AUTHOR: NORTH CAROLINA AGRICULTURAL AND TECHNICAL STATE
--      UNIV  GREENSBORO SCHOOL OF ENGINEERING
-- 6 -  UNCLASSIFIED TITLE:     DESIGN AND TESTING OF SMALL COMPOSITE
--      SPECIMENS.
-- 9 -  DESCRIPTIVE NOTE: FINAL REPT., 1979-1981,
--10 -  PERSONAL AUTHORS: SHARMA,A. V. ;
--11 -  REPORT DATE:        DEC    , 1981
--12 -  PAGINATION:      73P
--15 -  CONTRACT NUMBER:  NSG-1631
--18 -  MONITOR ACRONYM:  NASA
--19 -  MONITOR SERIES:   CR-169059
--20 -  REPORT CLASSIFICATION:  UNCLASSIFIED
--22 -  LIMITATIONS (ALPHA):     APPROVED FOR PUBLIC RELEASE; DISTRIBUTION
--      UNLIMITED. AVAILABILITY: NATIONAL TECHNICAL INFORMATION SERVICE,
--      SPRINGFIELD, VA. 22161. N82-26393.
--33 -  LIMITATION CODES:  1  24


-- END              Y  FOR NEXT ACCESSION
```

ACKNOWLEDGMENTS

The financial support provided for this work by the National Aeronautics and Space Administration through a grant NSG-1631 is gratefully acknowledged. The author expresses his sincere appreciation to Mr. Marvin D. Rhodes, Technical Officer, of the Langley Research Center for his assistance in the development of the specimen support fixture and for rendering many valuable suggestions during the course of this investigation.

Design and Testing of Small Composite Specimens

ABSTRACT

An experimental investigation was conducted to study the effect specimen size on the buckling strains of liminates subjected to low velocity projectile impact. The fiber composite selected was T300/5208 graphite/epoxy system. The quasi-isotropic laminates tested had 16 and 32 plies. The results were compared with those of a 48-ply laminate tested elsewhere. Specimens of three different lengths with length to width aspect ratios of 1, 1.5 and 2 were also studied. The results show that (a) the specimen length does not have any significant influence on the buckling strains at failure caused by the projectile impact, (b) the influence of specimen thickness on the strains at failure would decrease as the velocity of the impacting projectile increases.

TABLE OF CONTENTS

LEGEND/ABBREVIATIONS

K.E	Kinetic Energy of the impacting projectile, J.
σ	Stress, MPa.
$\bar{\sigma}$	Maximum Stress (of undamaged specimen), MPa.
ε	Strain corresponding to σ.
$\bar{\varepsilon}$	Maximum Strain corresponding to $\bar{\sigma}$.
a	Nominal length of specimen, cm.
b	Nominal width of specimen, cm.
t	Nominal thickness of the specimen, cm.
●	Data point corresponding to catastropic failure.
ø	Data point corresponding to residual strength or strain of specimen surviving the impact.
o	Data Point corresponding to preload or prestrain applied to the specimen prior to impact.
i,r,u	Subscripts refer to values at impact, residual stage, ultimate or maximum values, respectively.

LIST OF TABLES

LIST OF FIGURES

List of Figures (Continued)

INTRODUCTION

The use of high-modulus fiber composites in the design of structural components of aircraft is increasing. One of the problems that need attention in such a design is the effect of low velocity projectile impact on the strength carrying ability of the composite structural components. If the structural components are to be subjected to compressive loads, the analysis of buckling failure modes is also important. The objective of the present work is to show any correlation that may exist between the results obtained from testing large thick panels and small thin panels. Earlier work by Rhodes [1]* addressed some aspects of the buckling strains in thicker composite laminates. Several types of failure modes in the thick compression panels were also identified in this study. With the results of this study in the background, the present study is directed to investigate the advantages, if any, in testing thinner laminates of variable lengths. The specimen stabilization and loading mechanism is similar to that used by Rhodes [1] and is shown in Figure 2.

* Numbers in the square brackets refer to references at end.

SPECIMENS AND EXPERIMENTAL ARRANGEMENT

All the specimens tested were identical with respect to material, orientation, stacking sequence and width with the exception of the thickness and the length. The material selected was graphite/epoxy (T300/5208) system. The orientation and stacking sequence were $(\pm45,0,90)_{4S}$ for the 32-ply A Series laminates and $(\pm45,0,90)_{2S}$ for the 16-ply B Series laminates. Each lamina in the panel had a nominal cured thickness of $140\text{X}10^{-6}$m (0.0055 in.). The nominal dimensions of the specimens tested are shown in Table I. A sketch of the specimen indicating the unsupported and the supported dimensions is shown in Figure 1. A general specimen support and stabilization mechanism is shown in Figure 2. This supporting device was used in testing all the specimens. However, the side support bars and channel sections as shown in Figure 2, were of variable lengths to correspond with the respective specimen lengths. The projectile impact at low velocities was accomplished by using an air gun. The projectile is an aluminum sphere 1.27 cm (0.5 in.) in diameter. The projectile firing mechanism was described briefly by Sharma [2].

Static compressive loads were applied to the specimens using the specimen loading and stabilizing device as shown in Figure 2. In this figure, only the bottom support plates are shown. The top support plates (not shown) are similar to the bottom support plates (D & E). The side support bar (A) and the channel (B) were designed to prevent the laminate from column-type failure under compressive loads. The bars, shown

as C (and there were four such bars - two in the bottom and two in the top) serve to prevent the side support mechanism from rotating (or tilting) in compression. The whole device was designed in such a way to accommodate the axial compressive deformation of the specimens. Detailed dimensions of the supporting device were shown in Ref. 3. The compressive loads and the resulting strains were recorded using the standard experimental techniques. The axial strains were measured using four strain gages. Two of these gages were bonded on the front plane and two at the corresponding points on the back plane. Moreover, the gages were located at points on the specimen away from the physical constraints imposed on the specimen by the supporting and loading mechanism. Several undamaged specimens in each of the series were tested to determine the compressive axial strains and the corresponding loads. Some of the specimens were subjected to varying magnitudes of preloads prior to the projectile impact. The magnitude of the preload applied to the specimen was less than the maximum compressive load. Depending on the magnitude of the preload, some specimens failed catastrophically upon impact. Loading was continued on those specimens that survived the impact to determine the residual strength of the impact-damaged specimens. The term "failure threshold" used in subsequent sections is defined as the lowest buckling load which precipitated catastrophic failure in the specimen at a given impact energy. The stress ratio, $\sigma/\bar{\sigma}$, used in this report is defined as the ratio of the stress in the specimen prior to impact, or the residual strength of the specimen, to the static buckling strength of the virgin specimen.

RESULTS AND ANALYSES

The nominal width of all the specimens was 7.62 cm (3.0 in.). In each of the Series labled as A and B, specimens of three different lengths with length to width aspect ratios of 1:1, 1.5:1, and 2:1 were tested. The total number of specimens tested in each of the series is shown in tabular form elsewhere in this report.

The numerical data fror testing the specimens are given in Tables II through XIII. The normalized values shown in these tables were obtained from dividing the magnitude of the appropriate variable by the corresponding average ultimate values of the undamaged specimens at failure. A few of the abnormal values observed in this process were discarded. These abnormal values were suspected to be the result of either inadvertent misalignment of the loading fixture or by not providing sufficient torque to the bolts that hold the specimen in the loading fixture. It may be remarked that those components of the loading and supporting device that come in contact with the specimen either before loading or during loading were provided with smooth rounded off edges in order to minimize any localized stress concentrations on the specimen.

The numerical data for each of the series of specimens tested is plotted as a function of the kinetic energy of the impacting projectile. The resulting graphs, for example, are shown in Figures 3-6 for the specimens in A 10 Series (aspect ratio 1:1, 32 plies). Based on the limited experimental data, a faired curve through the data points is drawn. This faired curve is designated as a failure threshold curve. The failure threshold curve may be

interpreted to demark the area of graphs shown in this report into two distinct zones, viz., the failure zone and the survival zone. Whenever the applied stress (or strain) level is above the failure threshold, the specimen would fail catastrophically upon impact at the impact energy level under consideration. From these faired failure threshold curves, it is possible to develop an approximate idea with regards to the residual strength of the impact-damaged laminates subjected to compressive loads. The graphs indicating the experimental data for the other series of specimens, A 15, A 20, B 10, B 15, and B 10 are shown in Figures 7-10, 11-14, 15-18, 19-22, and 23-26, respectively.

The primary objective of this study, as indicated earlier, is to observe any correlation that may exist in the buckling strains by testing laminates of various thicknesses and lengths. It was indicated by Rhodes [1] that width effects beyond a certain minimum specimen width (for example, width to projectile diameter ratio greater than 5) appear not to influence the buckling strains. Consequently, this study is directed towards varying the lengths and thicknesses of the laminates studied. The variation of strains at failure as a function of the total projectile impact energy for all the laminate series tested is shown in Figure 27. The data base for the curves in Figure 27 is generated from the respective faired (threshold) curves for each of the series tested. The NASA data (Ref. 1, Fig. 9, b, 48-ply quasi-isotropic laminate C) that is used in this report is similarly generated. The data base so generated is shown in Tables XIV and XV. Since the number of specimens tested for each series at any one energy level is limited,

the data generated from the faired curves is deemed to be a better representation of the laminate behavior. It may be noted that the magnitude of the impact-energy in the NASA study was at a relatively higher level than the impact energy level used in this study. Further, the number of plies in each of the series and that of NASA are 16 (B Series), 32 (A Series), and 48 (NASA), respectively. For the purpose of comparing the results, the impact-energy needed per ply to cause catastrophic failure at a particular strain level is assumed to be a common denominator for all the laminates. The derived strain data and the corresponding energy per ply for all the laminates are also shown in Tables XIV and XV. These results are plotted as shown in Figure 28.

By studying the series of graphs in Figure 28, a few observations may be made:

1. The laminates of A Series (32 plies) having the length to width aspect ratios of 1:1, 1.5:1, and 2:1 do not seem to have significant variation in their strain values (refer to <u>curves</u> 1, 2, and 3) at any one impact energy/ply level. A similar observation may also be with respect to the 16-ply laminates of B Series (refer to <u>curves</u> 4, 5 and 6). Since the specimen width is essentially a constant for all the laminates (Series A and B), the effect of length on the values of strains at failure for any <u>one</u> Series of laminates appears to be not significant. However, if the behavior of the two Series is observed in the low energy/ply range (less than about 0.05 J/ply), it may be seen that the thicker laminates

(A Series) are exhibiting slightly higher strains than the laminates of the B Series. This may be interpreted to mean that the 'additional' plies in the thicker laminate may be responsible for exhibiting higher stiffness at low impact energy levels. On the other hand, the 48-ply NASA laminate (curve 7, and also see Table XV or Ref. 1) does not exhibit higher failure strains for the controlled (virgin) specimens. Since data is not available, the shape of the curve 7, Fig. 28, between the energy/ply levels of 0 to about 0.09 J/ply is assumed. Some of these small differences in the results may be attributable to the small deviations (specimen supporting devices, effective width to projectile diameter ratios, etc.) that exist in testing the laminates of Series A and B and the NASA's laminates.

2. Between the impact energy/ply range of 0.05 J/ply to about 0.15 J/ply, the magnitude of strains at failure for all the laminates in Series A and B may be observed to be the same. It may be remarked that the strengthening effect of 'additional' plies in the laminates appear to be converging and tend to be asymptotic to the energy axis. It may be noted that all the curves, 1 through 7, appear to be converging to form a common asymptote as the impact energy/ply increases.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this investigation, the following conclusions can be drawn:

1. At constant thickness, the length to width aspect ratio of the laminates subjected to low velocity projectile impact does not seem to have any significant effect on the buckling strain values at failure.
2. The laminate thickness appears to have some influence on the failure buckling strains at low impact velocities. As the impact energy per ply increases, all the laminates, regardless of their thickness, show asymptotic buckling strain values at failure.

In order to ascertain the specimen size effects further on the buckling behavior of laminates subjected to low velocity projectile impact, it is recommended that:

1. all the laminates be tested using the same specimen support device and loading mechanism,
2. at least four thicknesses of the same stacking sequence be tested,
3. a large number of specimens per thickness be tested leading to the statistical analyses of the results,
4. the impact energy levels be varied in a systematic way from 0 to about 25 J, and
5. the projectile firing mechanism be improved to develop reliable predetermined energy levels.

REFERENCES

1. Rhodes, M. D., "Low Velocity Impact Damage in Graphite-Fiber Reinforced Epoxy Laminates", 34th Annual Conference, SPI, New Orleans, Louisiana, Jan./Feb., 1979.

2. Sharma, A. V., "Low Velocity Impact Tests on Fibrous Composite Sandwich Structures", Test Methods and Design Allowables for Fibrous Composites, ASTM STP 734, C. C. Chamis, Ed., American Society for Testing and Materials, 1981, pp. 54-70.

3. Sharma, A. V., "Design and Testing of Small Composite Specimens", Status Report, March, 1980, Department of Mechanical Engineering, N. C. A. & T. State University, Greensbobo, NC 27411.

TABLE I. DIMENSIONS OF THE SPECIMENS

Series Number	Number of Plies	Nominal Size a cm/in	Nominal Size b cm/in	Nominal Size t cm/in	Unsupported Size a cm/in	Unsupported Size b cm/in	Unsupported Size t cm/in
A1	32	8.89/3.5	7.62/3.0	0.448/0.176	6.35/2.5	6.35/2.5	0.448/0.176
A2		12.07/4.75			9.53/3.75		
A3		15.24/6.0			12.70/5.0		
B1	16	8.89/3.5		0.224/0.088	6.35/2.5		0.224/0.088
B2		12.07/4.75			9.53/3.75		
B3		15.24/6.0			12.70/5.0		

TABLE II. Experimental Data: A10 Series

Material: Graphite/Epoxy, T300/5208
Nominal Size: 3.5" x 3.0" x 0.160"
Orientation: $(\pm 45,0,90)_{4s}$ -32 plies

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
A 10-01	0.00 0.00							39.09 174.00	.0101	85.72 591.06
A 10-02	0.00 0.00							36.36 162.00	.0105	79.74 549.79
A 10-03	0.00 0.00							40.00 178.00	.0105	87.72 604.82
A 10-04	10.83 1.22	17.52 77.93	.0054	38.42 264.91	31.41 139.71	.0083	59.50 410.25			
A 10-05	6.22 .70	29.49 131.17	.0077	64.67 445.91						
A 10-06	10.16 1.14	24.00 106.75	.0063	52.63 362.89	39.76 176.85	.0113	75.30 519.19			
A 10-07	10.31 1.17	27.00 120.09	.0077	59.21 408.26	41.52 184.68	.0115	76.64 528.43			

TABLE II(Continued)

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
A 10-08	6.57 .74	30.00 133.44	.0078	65.79 453.62	38.28 170.27	.0101	72.50 499.89			
A 10-09	0.00 0.00							40.49 180.00	.0123	88.79 612.23
A 10-10	27.00 3.05	34.36 152.83	.0095	75.35 519.54						
A 10-11	26.28 2.97	30.97 137.75	.0083	67.92 468.28						
A 10-12	27.00 3.05	26.14 116.27	.0072	57.32 395.25						
A 10-13	17.28 1.95	18.06 80.33	.0048	39.61 273.08	28.22 125.52	.0077	61.89 426.70			
A 10-14	26.64 3.01	22.14 98.48	.0059	48.55 334.77						
A 10-15	26.28 2.97	19.22 85.49	.0051	42.15 290.62						

TABLE II(Continued)

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
A 10-16	33.87	17.37		38.09						
	3.83	77.26	.0045	262.65						
A 10-17	6.57	20.00		43.86	32.27		70.77			
	.74	88.96	.0056	302.41	143.54	.0095	487.94			
A 10-18	6.93	26.00		57.02	42.70		93.64			
	.78	115.65	.0071	393.14	189.93	.0114	645.65			
A 10-19	10.38	34.11		74.80						
	1.17	152.72	.0093	515.76						
A 10-20	14.26	32.27		70.77						
	1.61	143.54	.0090	487.94						
A 10-21	8.67	30.20		66.23	38.77		85.02			
	.98	134.33	.0085	456.64	172.45	.0114	586.23			
A 10-23	10.16	9.00		19.74	32.39		71.03			
	1.15	40.00	.0023	136.09	144.07	.0084	489.76			
A 10-24	14.52	10.00		21.93	19.90		43.64			
	1.64	44.48	.0025	151.21	88.52	.0052	300.90			

TABLE II(continued)

Specimen Number	K.E. in - lb joule	P_i kips kN	ϵ_i	σ_i ksi MPa	P_r kips kN	ϵ_r	σ_r ksi MPa	P_u kips kN	ϵ_u	σ_u ksi MPa
A 10-25	24.20 2.73	12.00 53.38	.0029	26.32 181.45	36.35 161.68	.0108	79.71 549.63			
A 10-26	20.28 2.29	15.00 66.72	.0036	32.89 226.81	30.75 136.78	.0076	67.43 464.96			
A 10-27	96.79 10.94	16.05 71.17	.0040	35.20 242.69						
A 10-28	18.45 2.08	15.00 66.72	.0037	32.89 226.81	36.70 163.24	.0097	80.48 554.93			
A 10-29	23.86 2.70	20.00 88.96	.0050	43.86 302.41	34.70 154.35	.0093	76.10 524.69			
A 10-30	107.28 12.12	15.00 66.72	.0037	32.89 226.81						
A 10-31	13.23 1.49	20.00 88.96	.0027	43.86 302.41	34.70 154.35	.0100	76.10 524.69			

TABLE III. Normalized Data: A10 Series

Series: A 10
Avg. Ult. Load: 173.5 kN
Avg. Ult. Stress: 589.475 MPa
Avg. Ult. Strain: .01085

Specimen Number	Normalized Strain			Normalized Stress		
	ε_i	ε_r	ε_u	σ_i	σ_r	σ_u
A 10-01			.9309			1.0027
A 10-02			.9677			.9327
A 10-03			.9677			1.0260
A 10-04	.4977	.7650		.4494	.6960	
A 10-05	.7097			.7565		
A 10-06	.5806	1.0410		.6156	.8808	
A 10-07	.7097	1.0600		.6926	.8964	
A 10-08	.7189	.9309		.7695	.8480	
A 10-09			1.1340			1.0390
A 10-10	.8756			.8814		
A 10-11	.7650			.7944		
A 10-12	.6636			.6705		
A 10-13	.4424	.7097		.4632	.7239	
A 10-14	.5438			.5679		
A 10-15	.4700			.4930		
A 10-16	.4147			.4456		
A 10-17	.5161	.8755		.5130	.8278	
A 10-18	.6544	1.0510		.6669	1.0950	
A 10-19	.8571			.8749		
A 10-20	.8295			.8278		

TABLE III (Continued)

Specimen Number	Normalized Strain			Normalized Stress		
	ε_i	ε_r	ε_u	σ_i	σ_r	σ_u
A 10-21	.7834	1.0510		.7747	.9945	
A 10-23	.2120	.7742		.2309	.8308	
A 10-24	.2304	.4793		.2565	.5105	
A 10-25	.2673	.9954		.3078	.9324	
A 10-26	.3318	.7005		.3848	.7888	
A 10-27	.3687			.4117		
A 10-28	.3410	.8940		.3848	.9414	
A 10-29	.4608	.8571		.5130	.8901	
A 10-30	.3410			.3848		
A 10-31	.2488	.9217		.5130	.8901	

TABLE IV. Experimental Data: A 15 Series

Material: Graphite/Epoxy, T300/5208
Nominal Size: 4.5" x 3.0" x 0.160"
Orientation: $(\pm 45,0,90)_{4s}$ -32 plies

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
A 15-01	0.00 0.00							15.88 70.63	.0048	31.32 215.96
A 15-02	0.00 0.00							17.42 77.48	.0046	34.36 236.91
A 15-03	0.00 0.00							38.65 171.92	.0113	76.23 525.62
A 15-04	27.83 3.14	14.72 65.47	.0035	29.03 200.19						
A 15-05	13.03 1.47	10.00 44.48	.0027	19.72 136.00	25.89 115.16	.0071	51.07 352.09			
A 15-06	11.86 1.34	18.00 80.06	.0048	35.50 244.79	36.62 162.89	.0107	72.23 498.02			
A 15-07	57.76 6.53	24.29 108.04	.0065	47.91 330.33						

TABLE IV (Continued)

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
A 15-08	15.61 1.76	34.76 114.04	.0084	68.56 472.72						
A 15-09	16.79 1.90	20.00 88.96	.0053	39.45 271.99	30.56 135.93	.0085	60.28 415.60			
A 15-10	2.19 .25	15.00 66.72	.0040	29.59 203.99	36.32 161.55	.0104	71.64 493.94			
A 15-11	3.59 .41	15.00 66.72	.0039	29.59 203.99	30.43 135.35	.0085	60.02 413.84			
A 15-12	24.99 2.82	9.00 40.03	.0024	17.75 122.40	16.90 75.17	.0044	33.33 229.83			
A 15-13	110.90 12.53	8.00 35.58	.0022	15.78 108.80	10.25 45.59	.0029	20.22 139.40			
A 15-14	0.00 0.00							25.22 112.20	.0067	49.74 342.98

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE V. Normalized Data: A 15 Series

Series: A 15
Avg. Ult. Load: 171.92 kN
Avg. Ult. Stress: 525.62 MPa
Avg. Ult. Strain: .0113

Specimen Number	Normalized Strain			Normalized Stress		
	ε_i	ε_r	ε_u	σ_i	σ_r	σ_u
A 15-01			.4248			.4109
A 15-02			.4071			.4507
A 15-03			1.0000			1.0000
A 15-04	.3097			.3809		
A 15-05	.2389	.6283		.2587	.6698	
A 15-06	.4248	.9469		.4657	.9475	
A 15-07	.5752			.6284		
A 15-08	.7433			.8993		
A 15-09	.4690	.7522		.5175	.7907	
A 15-10	.3540	.9203		.3881	.9397	
A 15-11	.3451	.7522		.3881	.7873	
A 15-12	.2124	.3894		.2329	.4372	
A 15-13	.1947	.2566		.2070	.2652	
A 15-14			.5929			.6525

TABLE VI. Experimental Data: A 20 Series

Material: Graphite/Epoxy, T300/5208
Nominal Size: 6.0" x 3.0" x 0.160"
Orientation: $(\pm 45,0,90)_{4s}$ -32 plies

Specimen Number	K.E. in-lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
A 20-01	0.00 0.00							16.14 71.80	.0042	32.02 220.80
A 20-02	0.00 0.00							17.42 77.50	.0052	34.56 238.32
A 20-03	14.92 1.69	8.00 35.60	.0017	15.87 109.44	12.27 54.60	.0026	24.35 167.86			
A 20-04	40.10 4.53	10.00 44.48	.0025	19.84 136.81	13.99 62.20	.0036	27.76 191.39			
A 20-05	13.05 1.47	13.00 57.80	.0032	25.79 177.85	29.39 130.70	.0075	58.31 402.07			
A 20-06	14.07 1.59	14.00 62.30	.0034	27.78 191.53	20.62 91.70	.0053	40.91 282.09			
A 20-07	22.85 2.58	17.30 78.90	.0048	34.33 236.67						

ABLE VI (Continued)

pecimen umber	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
20-08	50.43 5.70	16.20 72.10	.0041	32.14 221.63						
20-09	96.79 10.94	13.00 57.80	.0032	25.79 177.85						
20-10	0.00 0.00							38.28 170.30	.0100	75.95 523.69
20-11	14.26 1.61	25.00 111.20	.0065	49.60 342.01	36.32 161.60	.0099	72.06 496.88			
20-12	23.86 2.70	10.00 44.48	.0025	19.84 136.81	24.17 107.50	.0062	47.96 330.66			
20-13	0.00 0.00							39.02 173.60	.0110	77.42 533.82
20-14	21.87 2.47	10.00 44.48	.0024	19.84 136.81	24.48 108.90	.0058	48.57 334.90			

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE VII. Normalized Data: A 20 Series

Series: A 20
Avg. Ult. Load: 171.95 kN
Avg. Ult. Stress: 528.76 MPa
Avg. Ult. Strain: .0105

Specimen Number	Normalized Strain			Normalized Stress		
	ε_i	ε_r	ε_u	σ_i	σ_r	σ_u
A 20-01			.4000			.4176
A 20-02			.4952			.4507
A 20-03	.1619	.2476		.2070	.3174	
A 20-04	.2381	.3428		.2587	.3620	
A 20-05	.3048	.7143		.3363	.7604	
A 20-06	.3238	.5048		.3622	.5335	
A 20-07	.4571			.4476		
A 20-08	.3905			.4191		
A 20-09	.3048			.3363		
A 20-10			.9523			.9904
A 20-11	.6190	.9428		.6468	.9397	
A 20-12	.2381	.5905		.2587	.6253	
A 20-13			1.0480			1.0090
A 20-14	.2286	.5524		.2587	.6334	

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE VIII. Experimental Data: B 10 Series

Material: Graphite/Epoxy, T300/5208
Nominal Size: 3.5" x 3.0" x .080"
Orientation: $(\pm 45,0,90)_{2s}$ -16 plies

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
B 10-01	0.00 0.00							10.55 46.93	.0064	40.89 281.95
B 10-02	0.00 0.00							8.83 39.28	.0060	34.22 235.98
B 10-03	0.00 0.00							7.31 32.51	.0040	28.33 195.36
B 10-04	38.88 4.39	4.00 17.79	.0026	15.50 106.90	4.46 19.84	.0031	17.29 119.19			
B 10-05	48.48 5.47	4.90 21.80	.0025	18.99 130.95						
B 10-06	0.00 0.00							13.42 59.69	.0094	52.02 358.65
B 10-07	26.28 2.97	6.38 28.38	.0033	24.73 170.50						

TABLE VIII(Continued)

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
B 10-08	36.71 4.15	5.64 25.09	.0032	21.86 150.73						
B 10-09	11.26 1.27	4.00 17.79	.0022	15.50 106.90	9.76 43.41	.0057	37.83 260.83			
B 10-10	11.60 1.31	4.50 20.02	.0027	17.44 120.26	6.87 30.56	.0041	26.63 183.60			
B 10-11	11.38 1.29	5.00 22.24	.0025	19.38 133.62	6.62 29.45	.0039	25.66 176.92			
B 10-12	0.00 0.00							14.57 64.81	.0086	56.47 389.38
B 10-13	13.74 1.55	7.36 32.74	.0041	28.53 196.69						
B 10-14	9.29 1.05	11.04 49.11	.0057	42.79 295.04						
B 10-15	0.00 0.00							9.70 43.15	.0052	37.60 259.23

ORIGINAL PAGE IS OF POOR QUALITY

TABLE VIII (Continued)

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
B 10-16	5.44 .62	10.00 44.48	.0054	38.76 264.25	14.45 62.27	.0095	56.00 386.17			
B 10-17	4.32 .49	12.40 55.16	.0059	48.06 331.39	13.74 61.12	.0085	53.26 367.20			
B 10-18	0.00 0.00							12.50 55.60	.0071	48.45 334.06
B 10-19	21.07 2.38	3.55 15.79	.0019	13.76 94.87	7.13 31.71	.0038	27.64 190.55			
B 10-20	17.86 2.02	3.00 13.34	.0016	11.63 80.17	6.99 31.09	.0038	27.09 186.81			
B 10-21	0.00 0.00							13.25 58.94	.0079	51.36 354.10

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE IX. Normalized Data: B 10 Series

Series B 10
Avg. Ult. Load: 59.76
Avg. Ult. Stress: 359.0: MPa
Avg. Ult. Strain: .00825

ORIGINAL PAGE IS OF POOR QUALITY

Specimen Number	Normalized Strain			Normalized Stress		
	ε_i	ε_r	ε_u	σ_i	σ_r	σ_u
B 10-01			.7757			.7853
B 10-02			.7273			.6572
B 10-03			.4848			.5441
B 10-04	.3151	.3757		.2977	.3319	
B 10-05	.3030			.3647		
B 10-06			1.1390			.9989
B 10-07	.4000			.4749		
B 10-08	.3879			.4198		
B 10-09	.2667	.6909		.2977	.7264	
B 10-10	.3273	.4970		.3349	.5113	
B 10-11	.3030	.4727		.3721	.4927	
B 10-12			1.0420			1.0840
B 10-13	.4970			.5478		
B 10-14	.6909			.8217		
B 10-15			.6303			.7220
B 10-16	.6545	1.1510		.7443	1.0750	
B 10-17	.7151	1.0300		.9230	1.0230	
B 10-18			.8606			.9304
B 10-19	.2303	.4606		.2642	.5307	
B 10-20	.1939	.4606		.2233	.5203	
B 10-21			.9576			.9862

TABLE X. Experimental Data: B 15 Series

Material: Graphite/Epoxy, T300/5208
Nominal Size: 4.5" x 3.0" x .080"
Orientation: $(\pm 45,0,90)_{2s}$ -16 plies

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
B 15-01	0.00 0.00							11.30 50.26	.0067	44.84 309.18
B 15-02	0.00 0.00							12.30 54.71	.0071	48.81 336.54
B 15-03	23.86 2.70	7.00 31.32	.0036	27.77 191.53						
B 15-04	28.09 3.17	5.00 22.24	.0025	19.84 136.81	5.20 23.13	.0027	20.63 142.28			
B 15-05	61.29 6.93	4.30 19.13	.0023	17.06 117.65						
B 15-06	15.87 1.79	3.00 13.34	.0015	11.90 82.08	8.20 36.47	.0044	32.54 224.36			
B 15-07	19.05 2.15	3.00 13.34	.0017	11.90 82.08	6.70 29.80	.0037	26.59 183.32			

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE X (Continued)

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
B 15-08	38.45 4.34	3.50 15.57	.0019	13.89 95.76	4.30 19.13	.0025	17.06 117.65			
B 15-09	19.66 2.22	4.00 17.79	.0023	15.87 109.44	6.90 30.69	.0039	27.38 188.79			
B 15-10	0.00 0.00							13.50 60.05	.0081	53.57 369.37
B 15-11	48.48 5.48	5.50 24.46	.0029	21.83 150.49						
B 15-12	66.37 7.50	3.00 13.34	.0017	11.90 82.08	4.25 18.90	.0021	16.87 116.28			
B 15-13	10.38 1.17	6.00 26.69	.0031	23.81 164.17	12.20 54.27	.0073	48.41 333.81			
B 15-14	28.09 3.17	7.10 31.58	.0037	28.17 194.26						

ORIGINAL PAGE IS OF POOR QUALITY

TABLE XI. Normalized Data: B15 Series

Series: B 15
Avg. Ult. Load: 55.00 kN
Avg. Ult. Stress: 338.36 MPa
Avg. Ult. Strain: .0073

Specimen Number	Normalized Strain			Normalized Stress		
	ε_i	ε_r	ε_u	σ_i	σ_r	σ_u
B 15-01			.9178			.9138
B 15-02			.9726			.9946
B 15-03	.4932			.5661		
B 15-04	.3425	.3699		.4043	.4205	
B 15-05	.3151			.3477		
B 15-06	.2054	.6027		.2426	.6631	
B 15-07	.2329	.5068		.2426	.5418	
B 15-08	.2603	.3425		.2830	.3477	
B 15-09	.3151	.5342		.3234	.5579	
B 15-10			1.1100			1.0920
B 15-11	.3973			.4448		
B 15-12	.2329	.2877		.2426	.3437	
B 15-13	.4247	1.0000		.4852	.9866	
B 15-14	.5068			.5741		

TABLE XII. Experimental Data: B 20 Series

Material: Graphite/Epoxy, T300/5208
Nominal Size: 6.0" x 3.0" x .080"
Orientation: $(\pm 45,0,90)_{2s}$ -16 plies

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
B 20-01	0.00 0.00							10.90 48.48	.0066	44.31 305.51
B 20-02	0.00 0.00							11.14 49.55	.0073	45.28 312.24
B 20-03	0.00 0.00							7.00 31.14	.0035	28.46 196.20
B 20-04	0.00 0.00							6.00 26.69	.0031	24.39 168.17
B 20-05	11.84 1.34	4.50 20.02	.0023	18.29 126.13	7.00 31.14	.0044	28.46 196.20			
B 20-06	38.62 4.36	6.38 28.38	.0034	25.93 178.82						
B 20-07	11.41 1.29	4.00 17.79	.0017	16.26 112.11	8.93 39.72	.0051	36.30 250.29			

ORIGINAL PAGE IS OF POOR QUALITY

TABLE XII (Continued)

Specimen Number	K.E. in - lb joule	P_i kips kN	ε_i	σ_i ksi MPa	P_r kips kN	ε_r	σ_r ksi MPa	P_u kips kN	ε_u	σ_u ksi MPa
B 20-09	12.39 1.40	6.00 26.67	.0027	24.39 168.17	10.06 44.75	.0053	40.89 281.96			
B 20-10	0.00 0.00							6.01 26.73	.0032	24.43 168.45
B 20-11	6.48 .73	7.00 31.14	.0027	28.46 196.20	12.35 54.93	.0079	50.20 346.15			
B 20-12	7.64 .86	8.50 37.81	.0047	34.55 238.24	10.00 44.48	.0057	40.65 280.28			
B 20-13	54.90 6.20	4.00 17.79	.0021	16.26 112.11	4.54 20.19	.0025	18.46 127.25			
B 20-14	7.19 .81	4.91 21.84	.0022	19.96 137.62						

TABLE XIII. Normalized Data: B 20 Series

Series: B 20
Avg. Ult. Load: 49.015 kN
Avg. Ult. Stress: 308.875 MPa
Avg. Ult. Strain: .00695

Specimen Number	Normalized Strain			Normalized Stress		
	ε_i	ε_r	ε_u	σ_i	σ_r	σ_u
B 20-01			.8633			.9891
B 20-02			1.0500			1.0110
B 20-03			.5036			.6352
B 20-04			.4460			.5444
B 20-05	.3309	.6331		.4083	.6352	
B 20-06	.4892			.5789		
B 20-07	.2446	.7338		.3629	.8103	
B 20-09	.3885	.7626		.5444	.9129	
B 20-10			.4604			.5454
B 20-11	.3885	1.1370		.6352	1.1210	
B 20-12	.6762	.8201		.7713	.9074	
B 20-13	.3021	.3597		.3630	.4120	
B 20-14	.3165			.4455		

TABLE XIV. Faired Data: Strains, K.E, K.E/ply

Series:	A 10		Series:	A 15	
Size:	3.5" x 3.0" x 0.160"		Size:	4.5" x 3.0" x .169"	
No. of Plies:	32		No. of Plies:	32	

Strain	K.E. joule	K.E./ply joule/ply	Strain	K.E. joule	K.E./ply joule/ply
.0098	0	0	.0112	0	0
.0075	1.250	.039	.0090	.312	.010
.0068	1.656	.052	.0068	1.000	.031
.0045	3.156	.099	.0060	1.312	.041
.0042	3.500	.109	.0045	2.000	.062
.0037	4.500	.141	.0038	2.500	.078
			.0030	3.562	.111

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XIV (Continued)

Series: A 20			Series: B 10		
Size: 6.0" x 3.0" x .168"			Size: 3.5" x 3.0" x .086"		
No. of Plies: 32			No. of Plies: 16		
Strain	K.E. joule	K.E./ply joule/ply	Strain	K.E. joule	K.E./ply joule/ply
.0115	0	0	.0075	0	0
.0090	.469	.015	.0068	.344	.021
.0075	1.000	.031	.0060	.653	.041
.0060	1.563	.049	.0051	1.000	.062
.0052	2.000	.062	.0034	2.000	.125
.0038	3.000	.094	.0030	2.594	.162
.0030	5.000	.156	.0026	5.000	.312

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XIV (Continued)

Series:	B 15		Series:	B 20	
Size:	4.5" x 3.0" x .084"		Size:	6.0" x 3.0" x .082"	
No. of Plies:	16		No. of Plies:	16	
Strain	**K.E. joule**	**K.E./ply joule/ply**	**Strain**	**K.E. joule**	**K.E./ply joule/ply**
.0075	0	0	.0070	0	0
.0060	.594	.037	.0060	.250	.016
.0052	1.000	.062	.0047	1.000	.062
.0036	2.000	.125	.0038	2.000	.125
.0030	2.562	.160	.0034	3.000	.188
.0028	3.000	.188	.0032	4.000	.250
.0011	5.000	.312	.0030	4.344	.271

TABLE XV. Faired Data: Strains, K.E/ply

Series: NASA (Ref. 1)
Size: 5" x 10" and 15" x 10"
Lamina Orientation: $(\pm 45,0,90,\mp 40,0,90)_{3S}$
No. of Plies: 48

Strain	K.E. joule	K.E./ply joule/ply
.0090	0	0
.0075	4.750	.099
.0060	7.000	.146
.0052	8.500	.177
.0040	11.200	.233
.0032	14.700	.306
.0028	19.500	.406

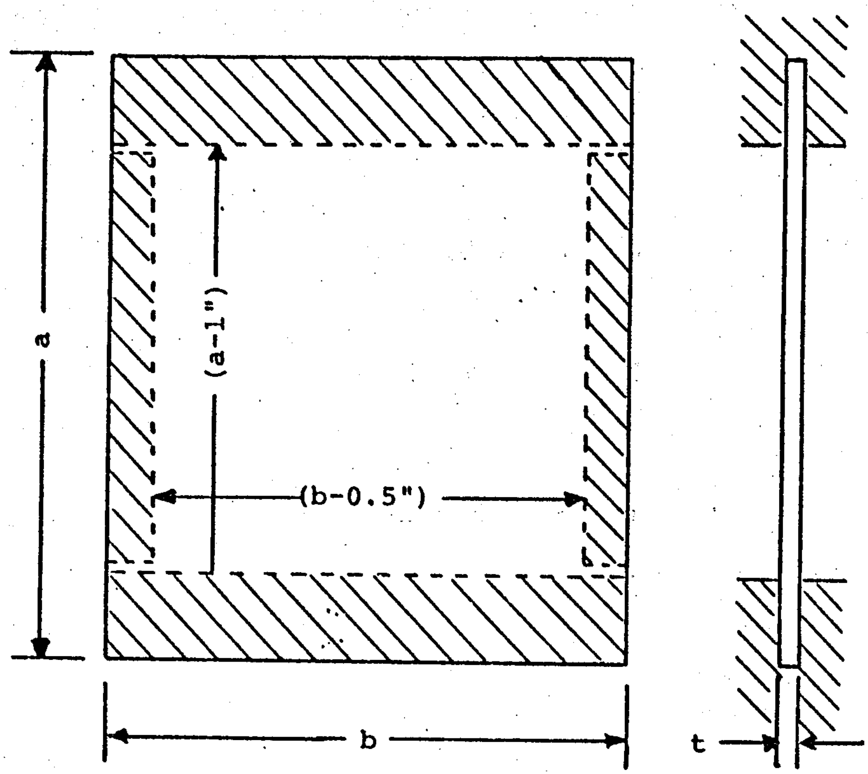
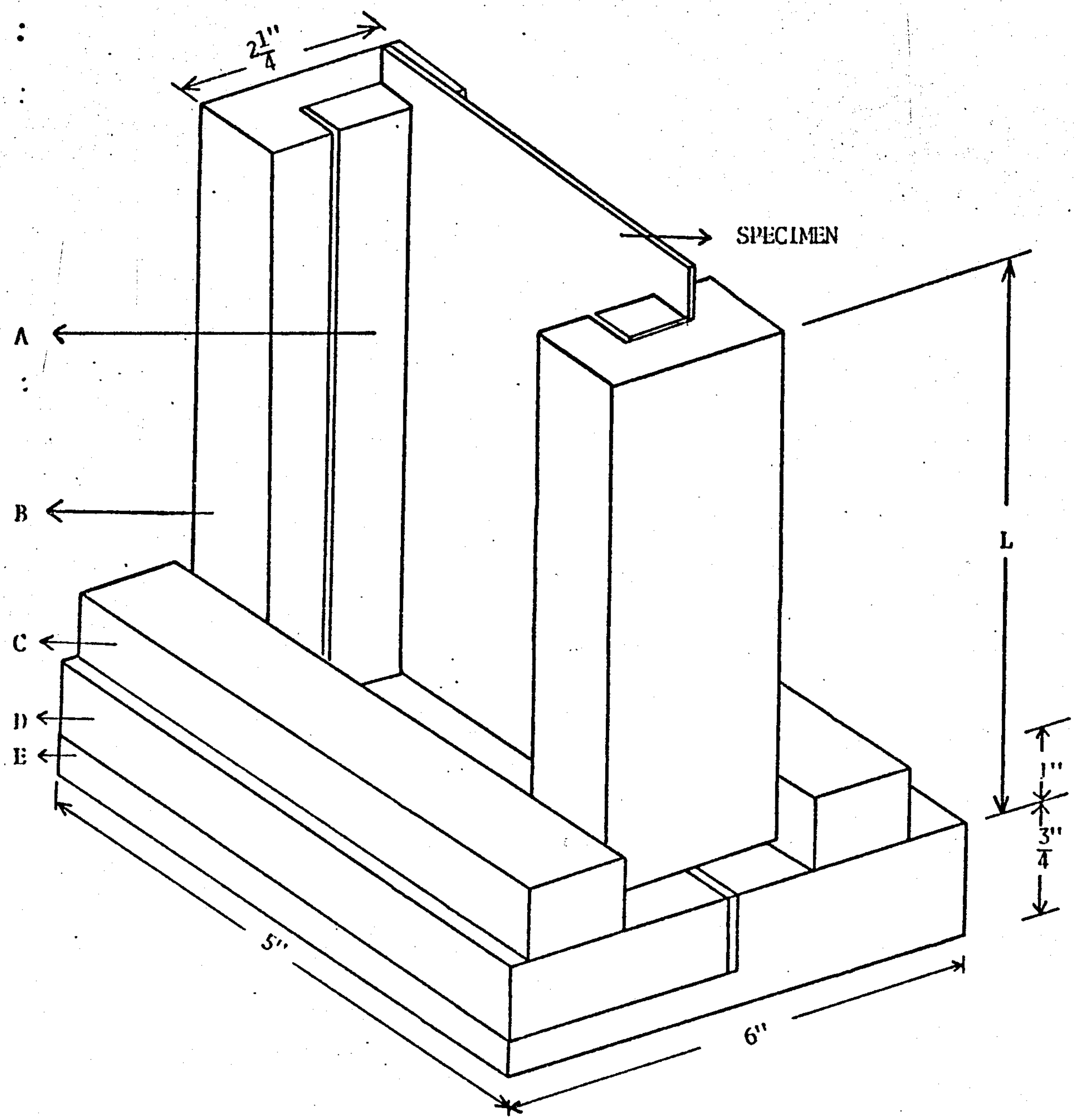


Figure 1. Nominal and Unsupported Specimen Size



A: SIDE SUPPORT BAR
B: SIDE SUPPORT CHANNEL
C: END SUPPORT BAR
D: END SUPPORT PLATE
E: MAIN SUPPORT PLATE

FIGURE 2. GENERAL VIEW OF SPECIMEN SUPPORTING DEVICE

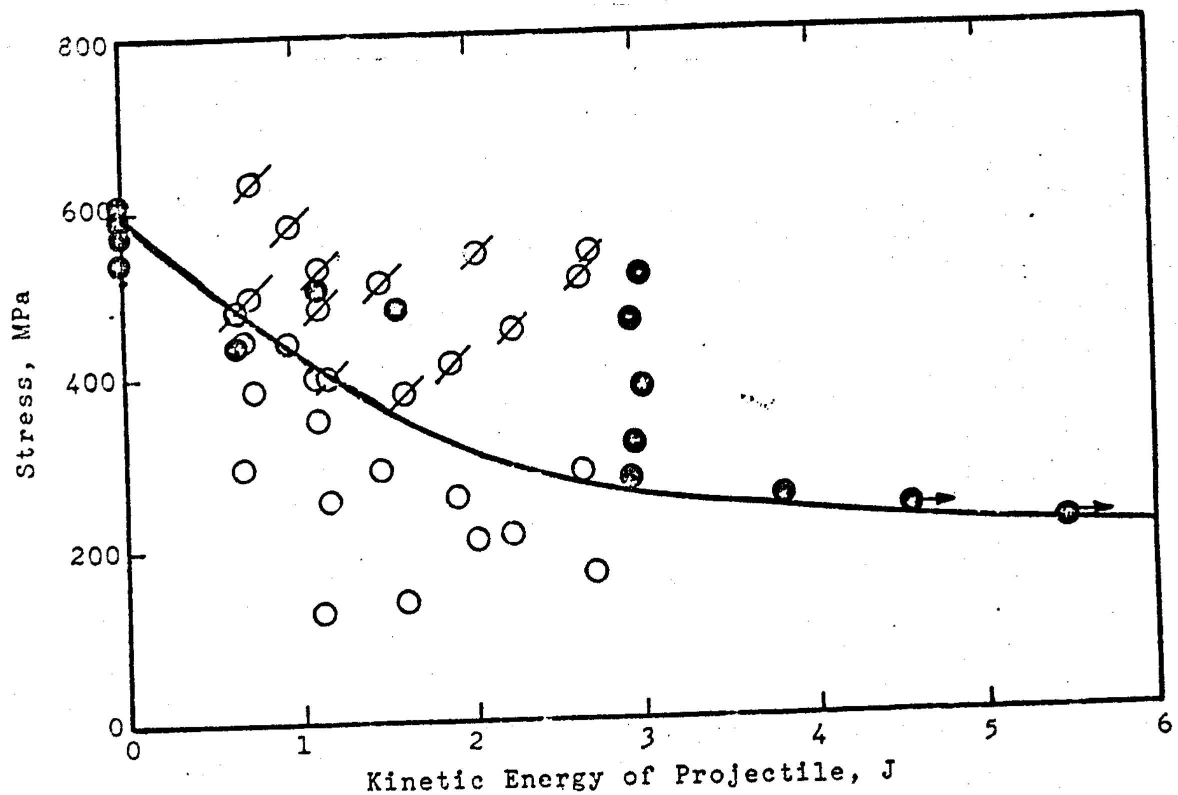


Figure 3. Stress vs. K.E. of Projectile - A 10 Series

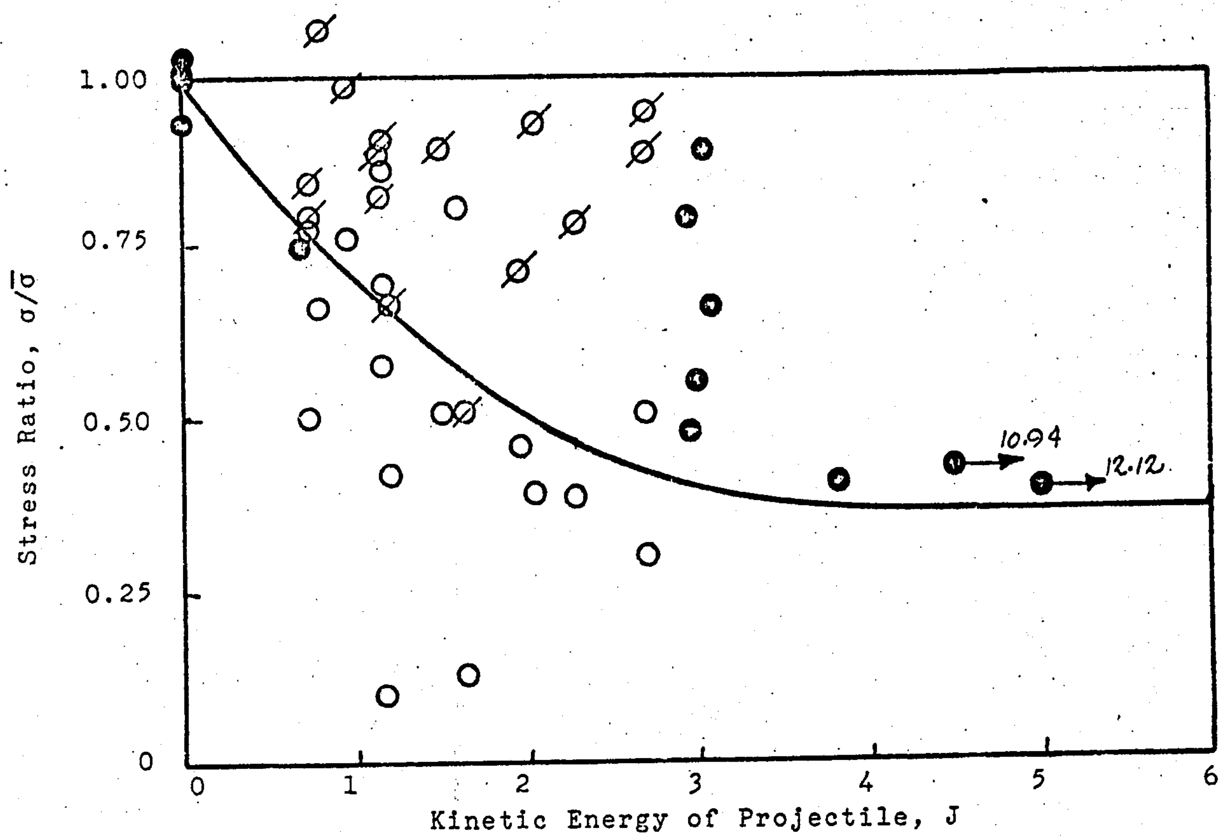


Figure 4. Normalized Stress vs. K.E. of Projectile: A 10 Series

ORIGINAL PAGE IS
OF POOR QUALITY

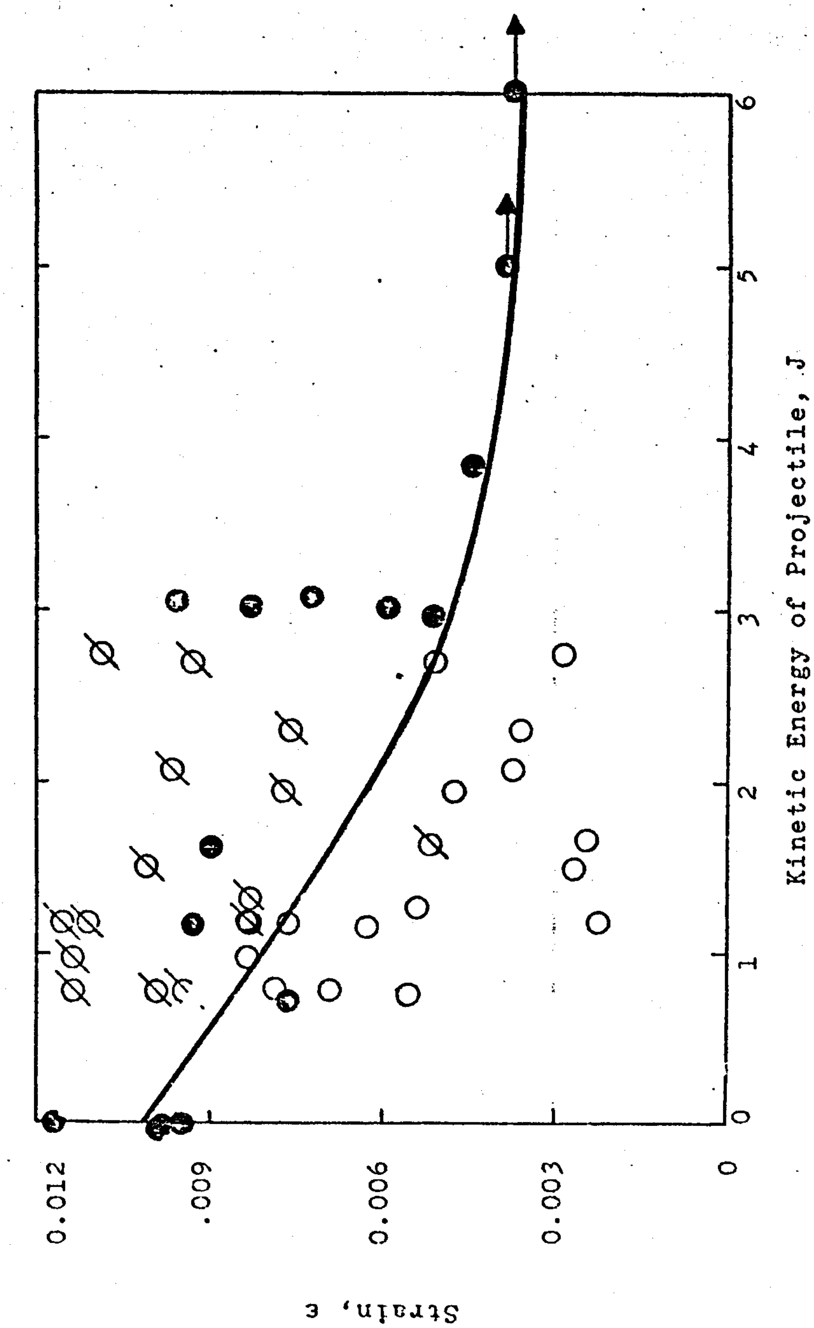


Figure 5. Strain vs K.E. of Projectile: A 10 Series

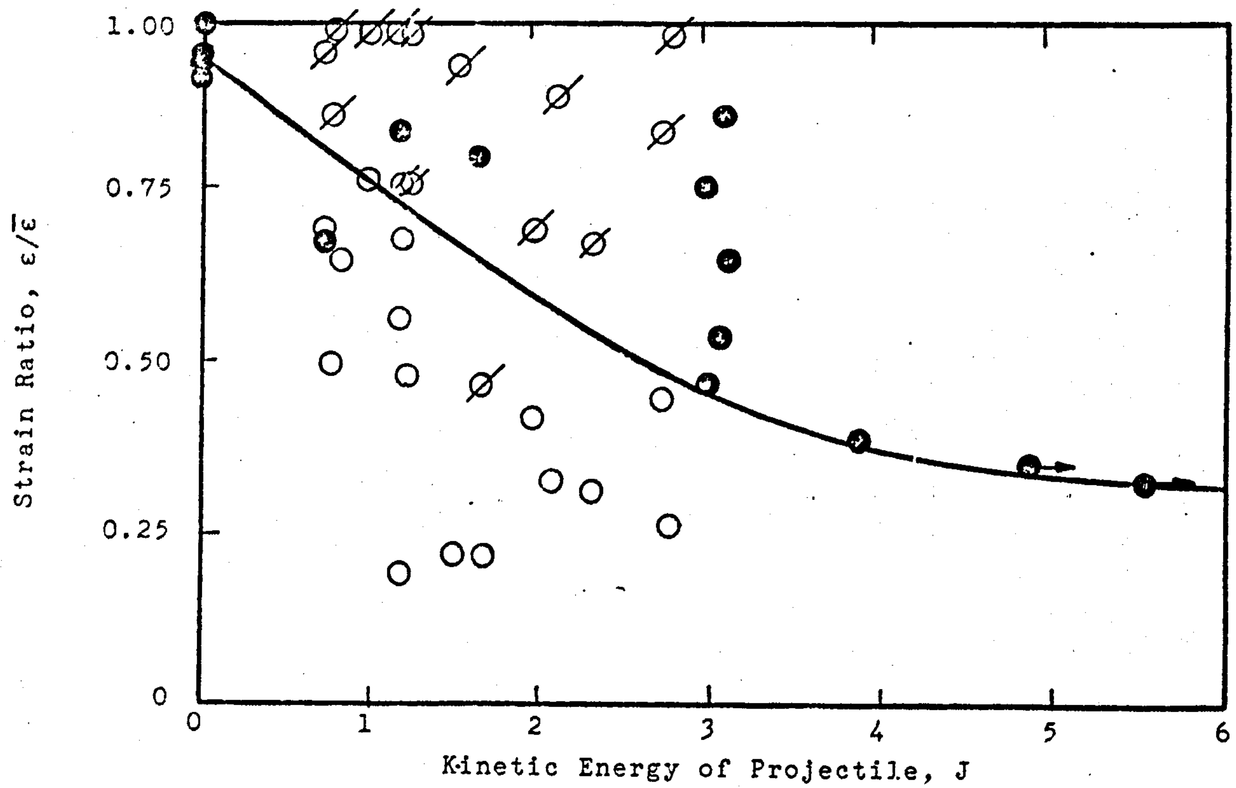


Figure 6. Normalized Strain vs. K.E. of Projectile: A 10 Series

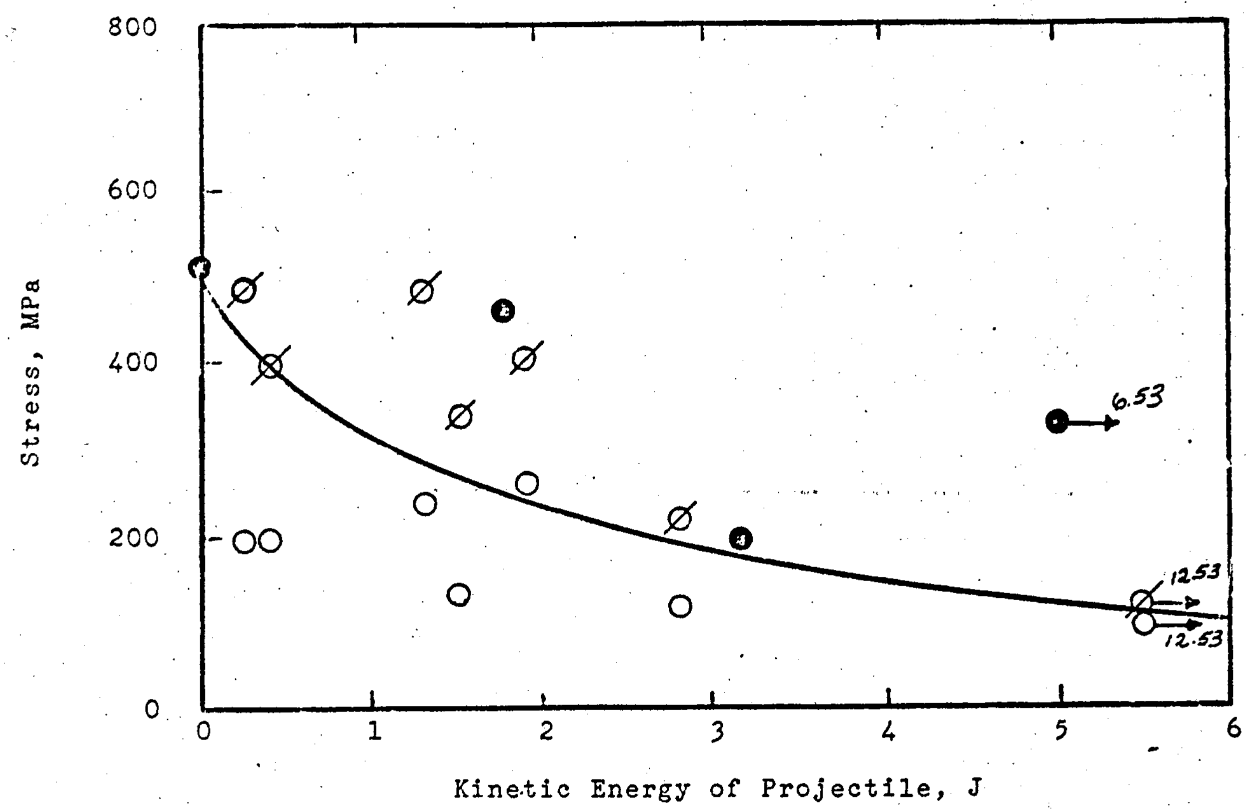


Figure 7. Stress vs. K.E. of Projectile: A 15 Series

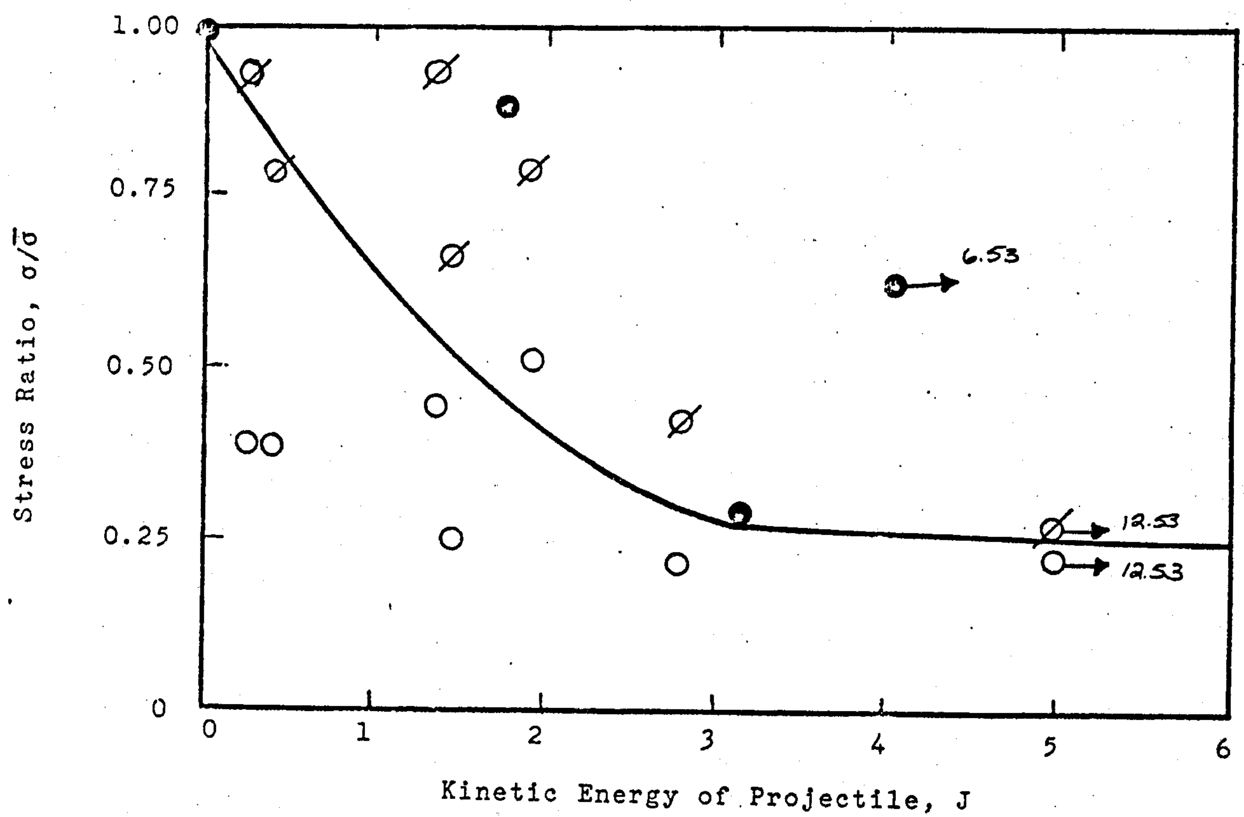


Figure 8. Normalized Stress vs. K.E. of Projectile: A 15 Series

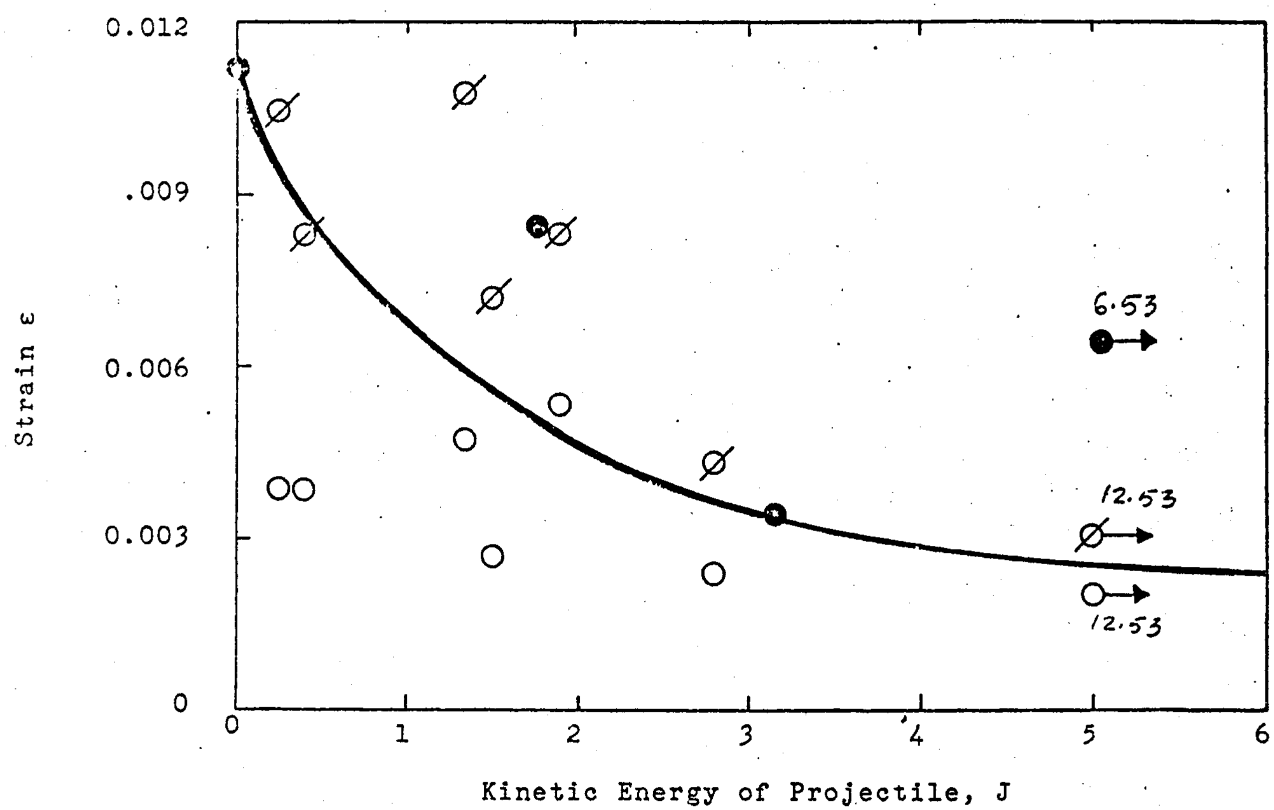


Figure 9. Strain vs. K.E. of Projectile: A 15 Series

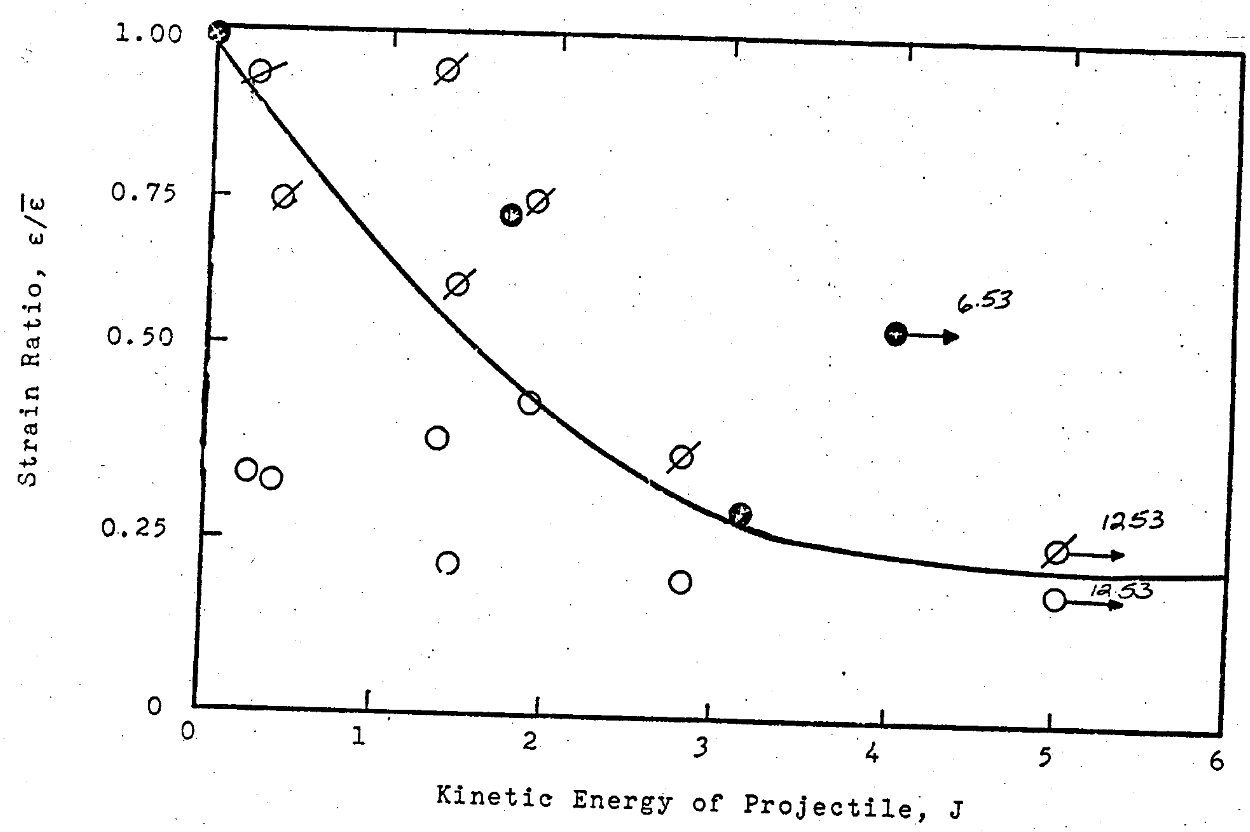


Figure 10. Normalized Strain vs. K.E. of Projectile: A 15 Series

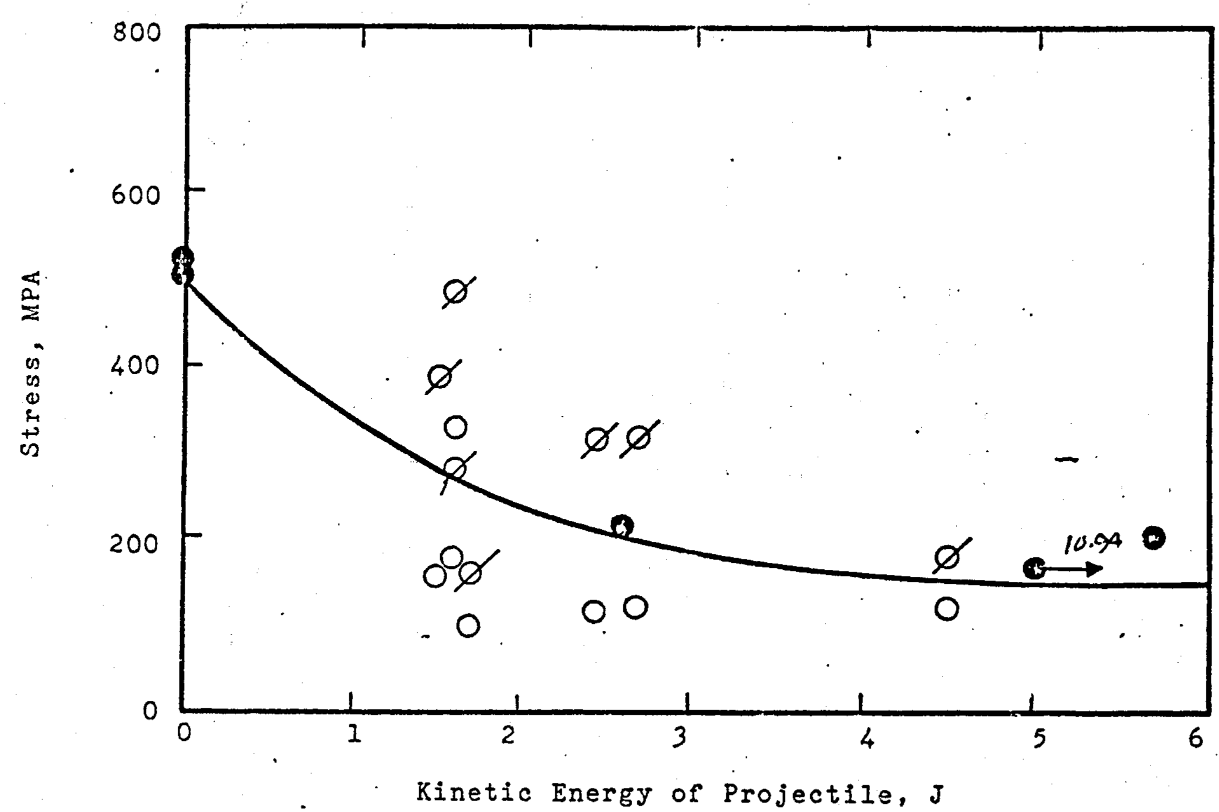


Figure 11. Stress vs. K.E. of Projectile: A 20 Series

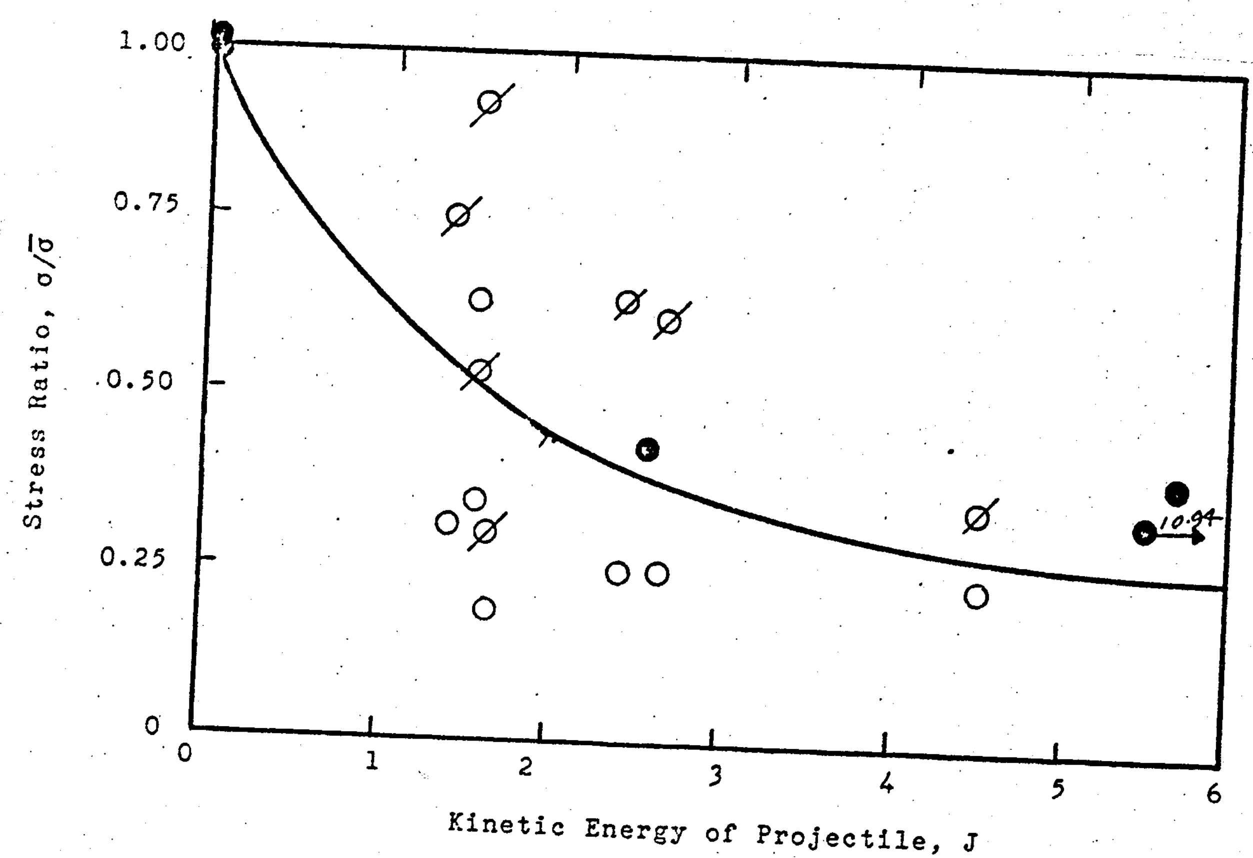


Figure 12. Normalized Stress vs. K.E. of Projectile: A 20 Series

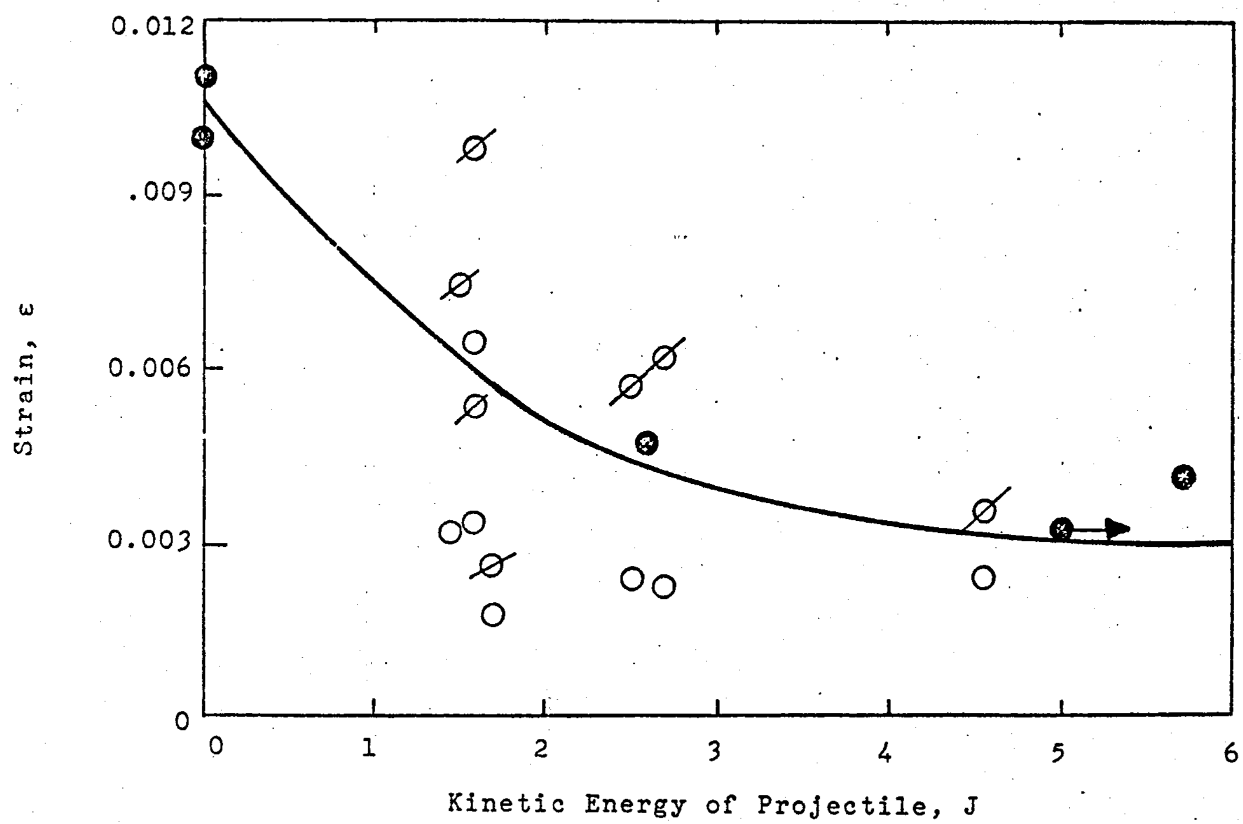


Figure 13. Strain vs. K.E. of Projectile: A 20 Series

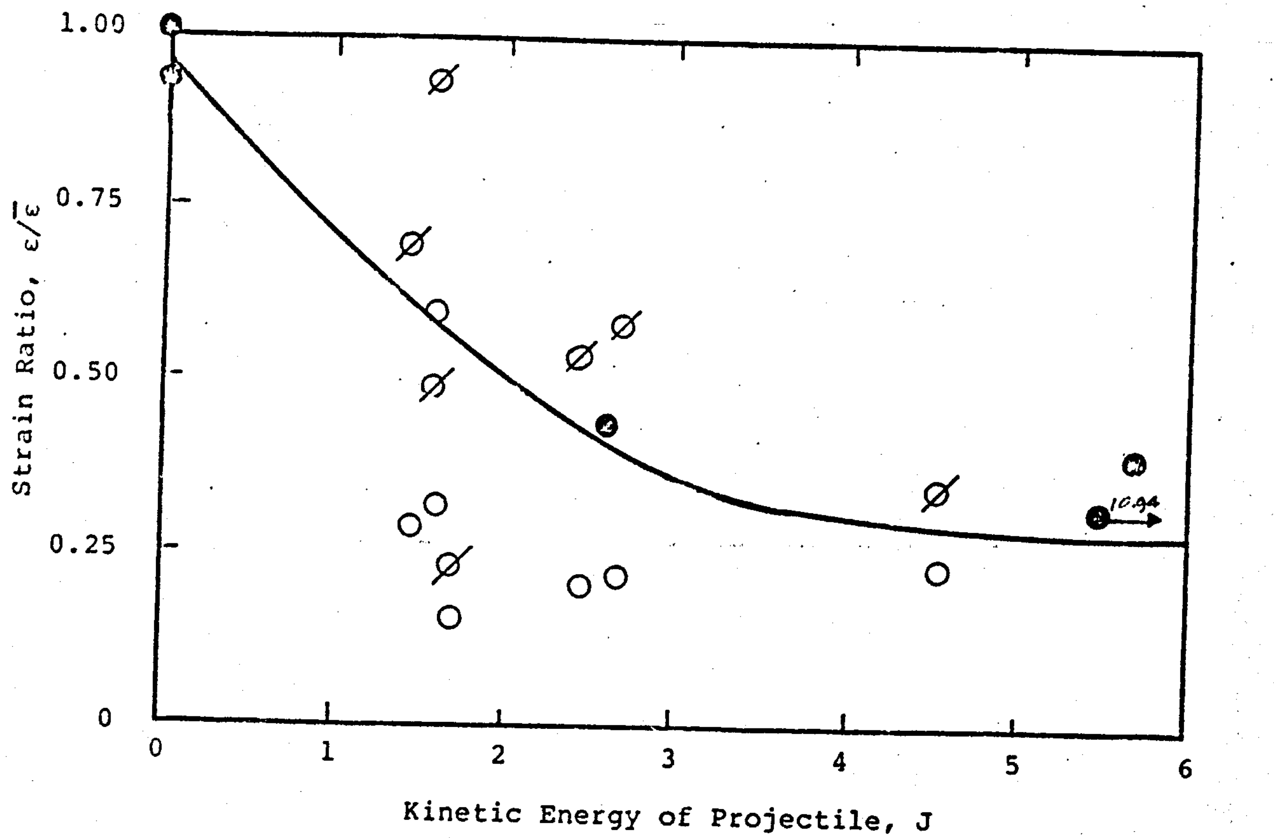


Figure 14. Normalized Strain vs. K.E of Projectile: A 20 Series

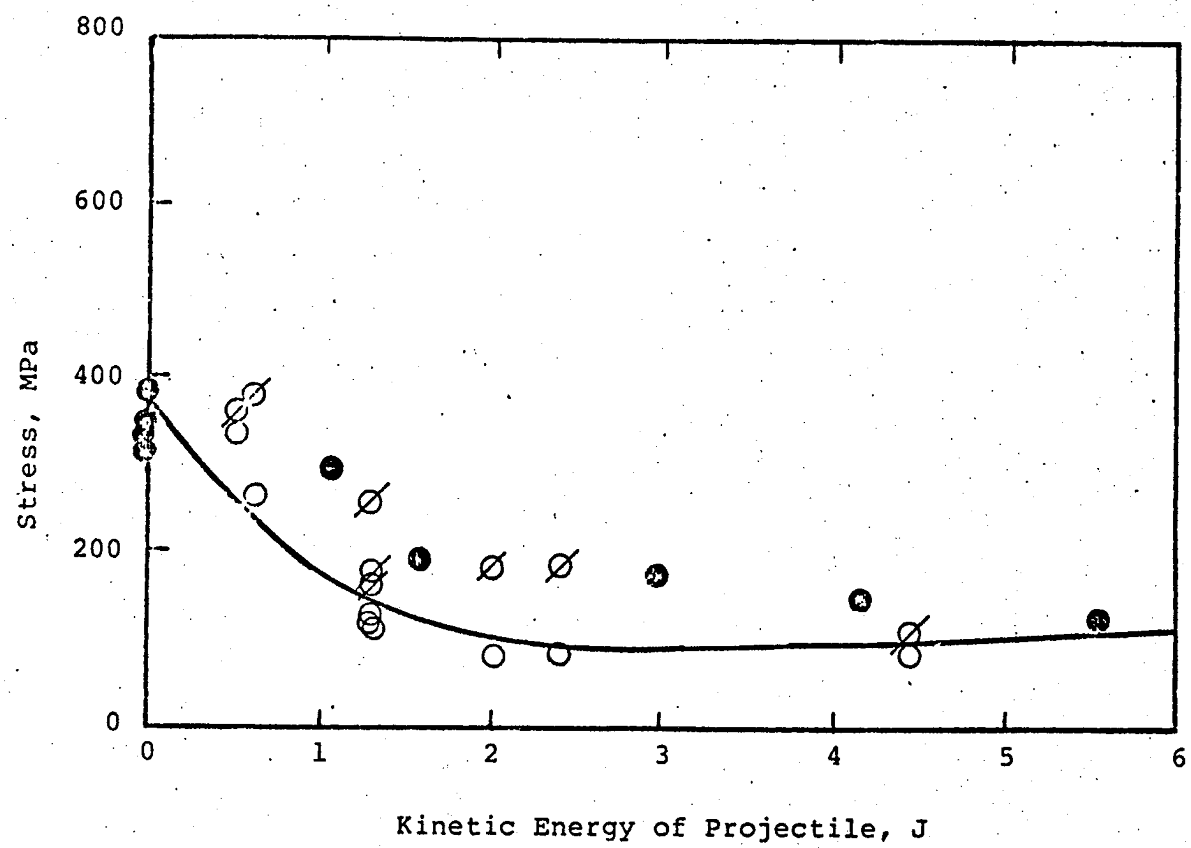


Figure 15. Stress vs. K.E of Projectile: B 10 Series

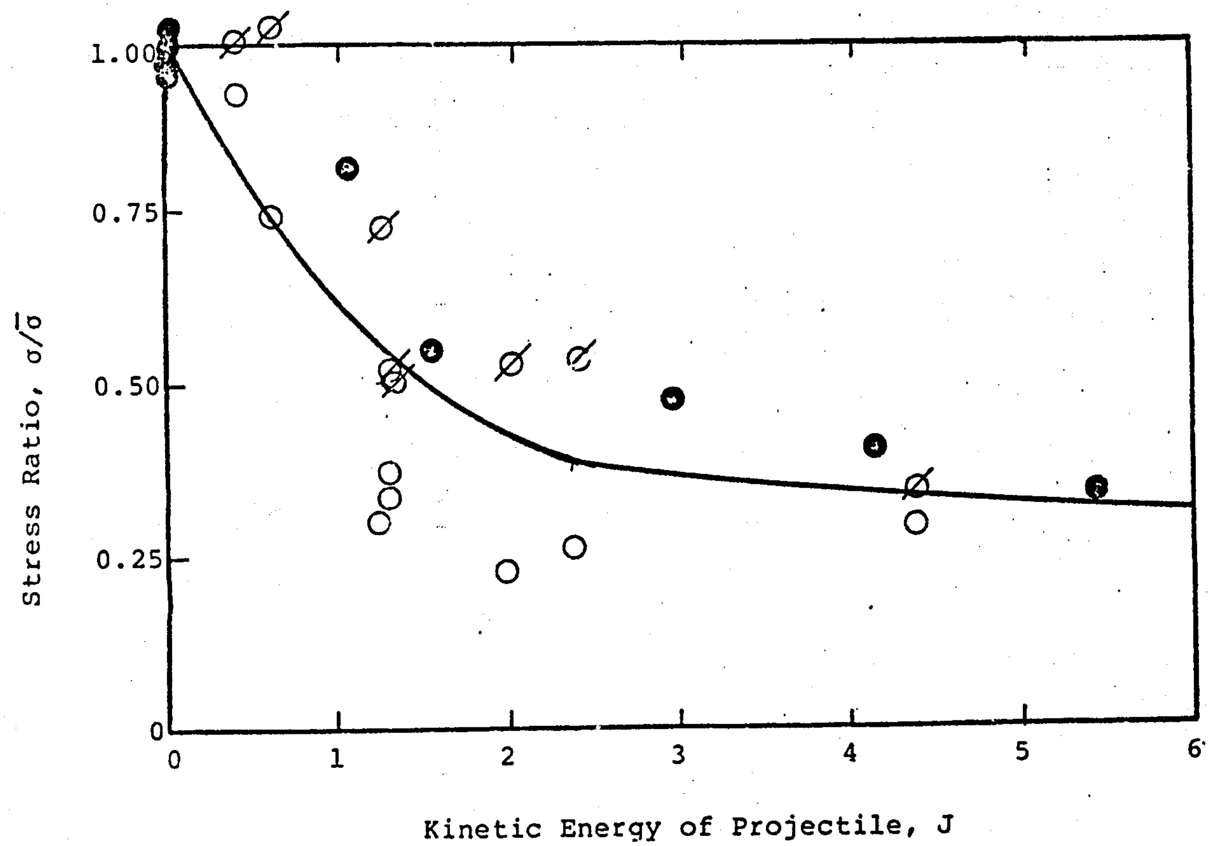


Figure 16. Normalized Stress vs. K.E of Projectile: B 10 Series

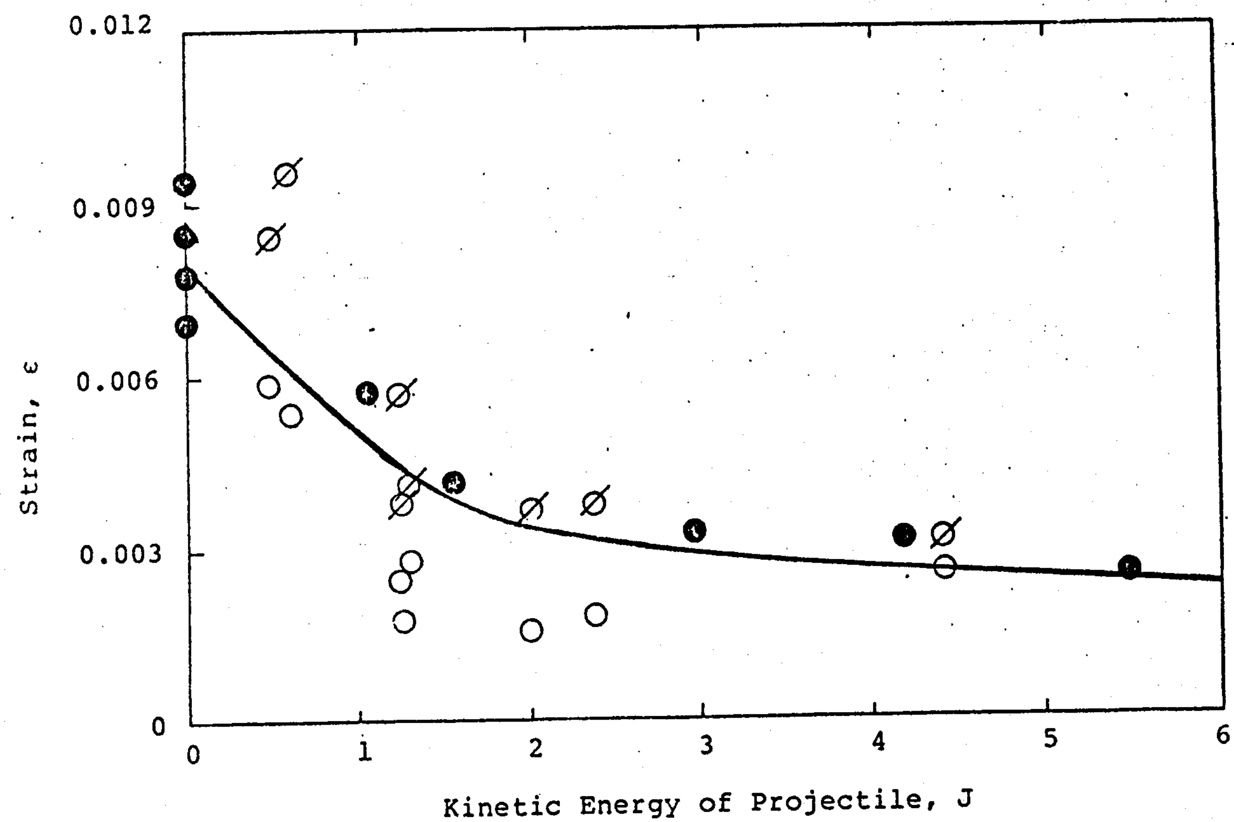


Figure 17. Strain vs. K.E of Projectile: B 10 Series

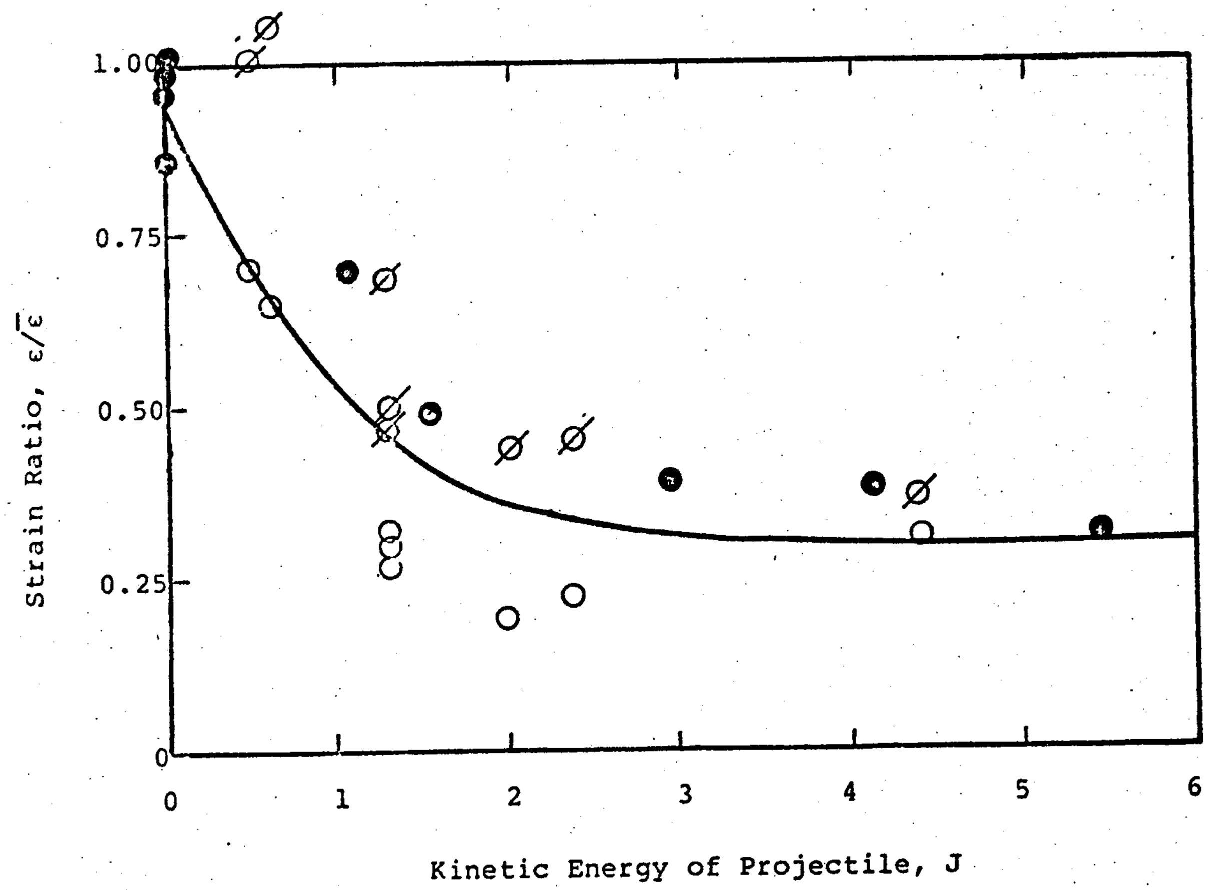


Figure 18. Normalized Strain vs. K.E of Projectile: B 10 Series

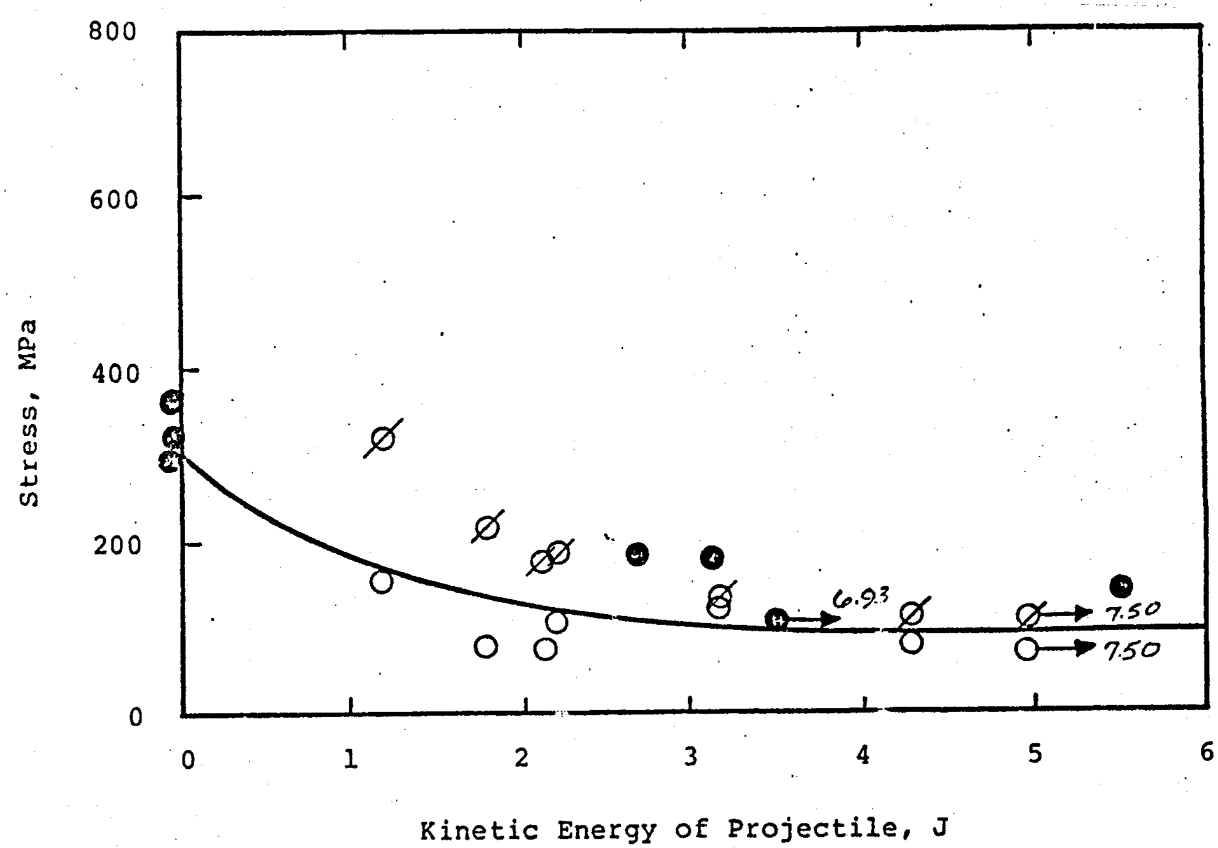


Figure 19. Stress vs. K.E of Projectile: B 15 Series

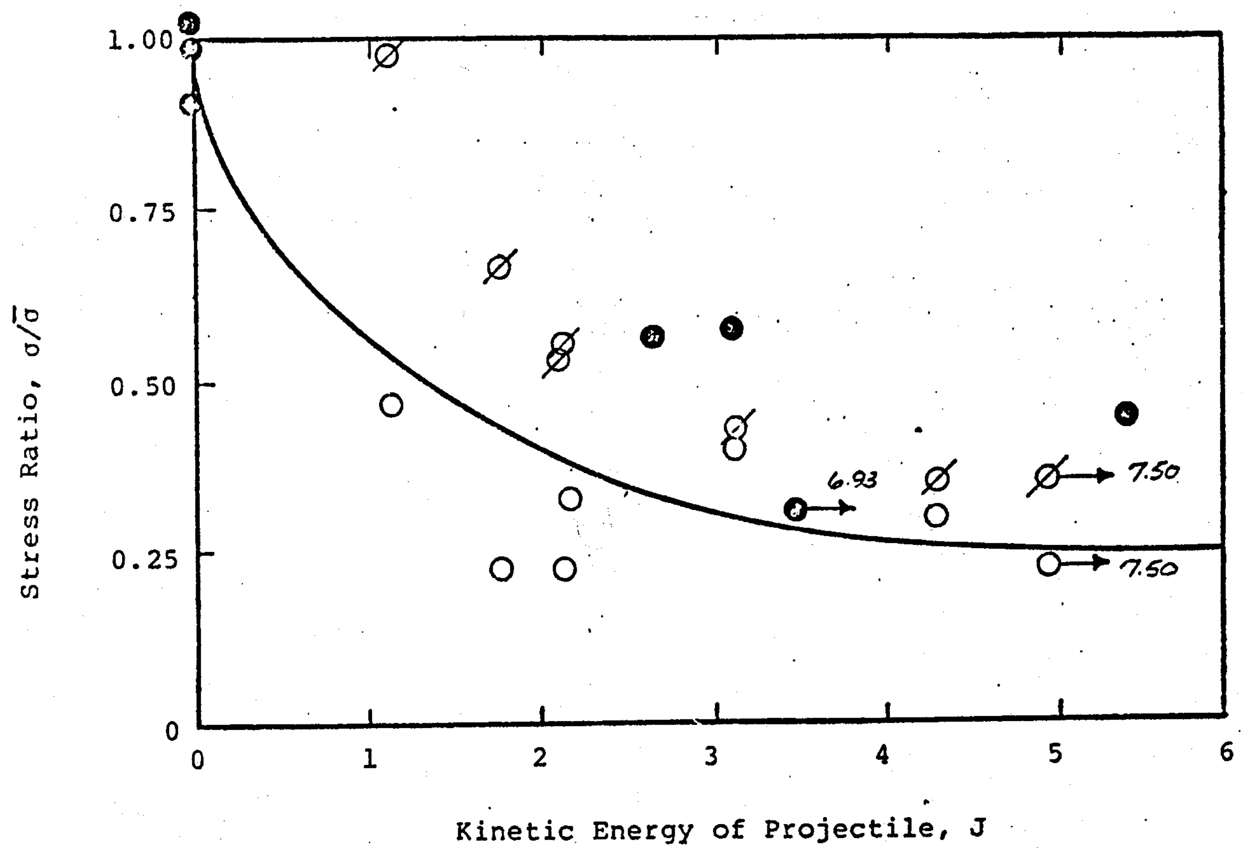


Figure 20. Normalized Stress vs. K.E of Projectile: B 15 Series

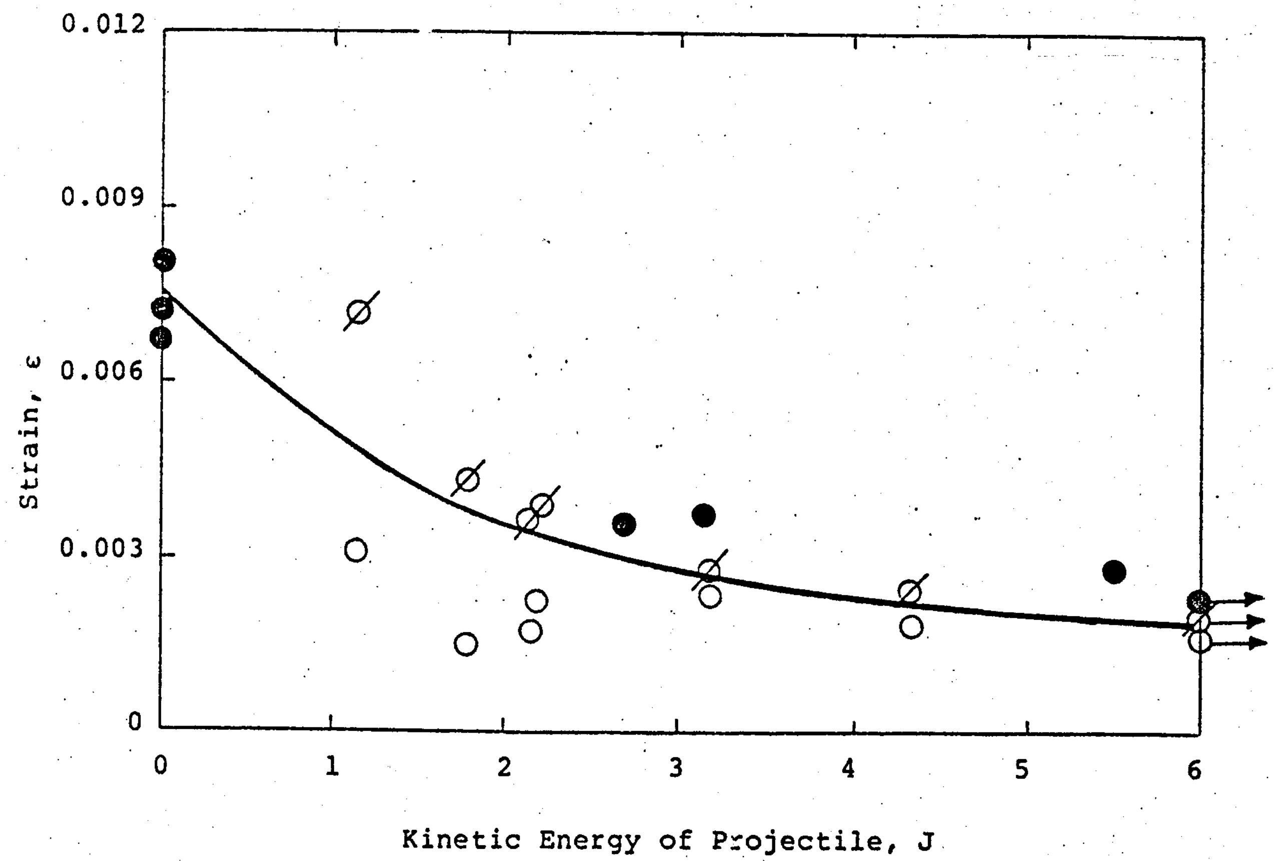


Figure 21. Strain vs. K.E of Projectile: B 15 Series

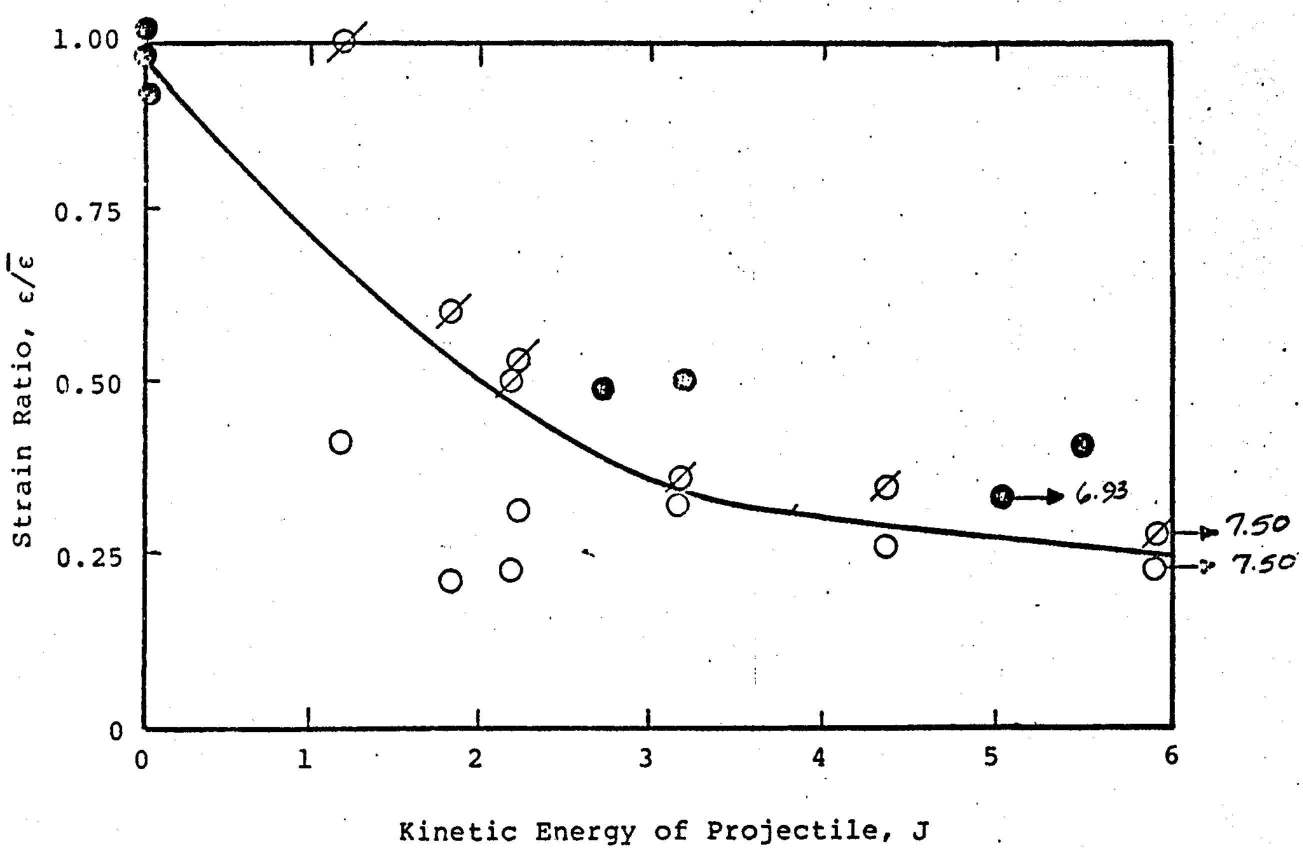


Figure 22. Normalized Strain vs. K.E of Projectile: B 15 Series

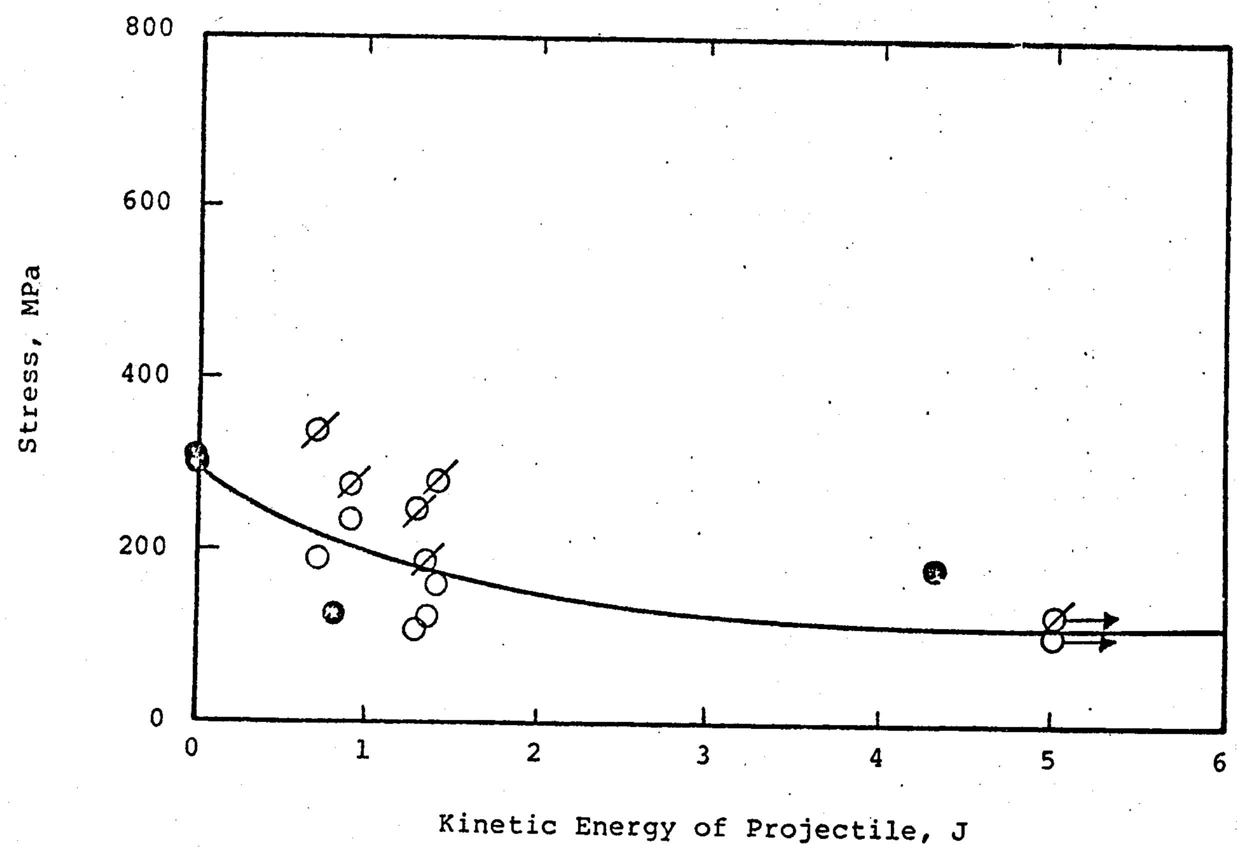


Figure 23. Stress vs. K.E of Projectile: B 20 Series

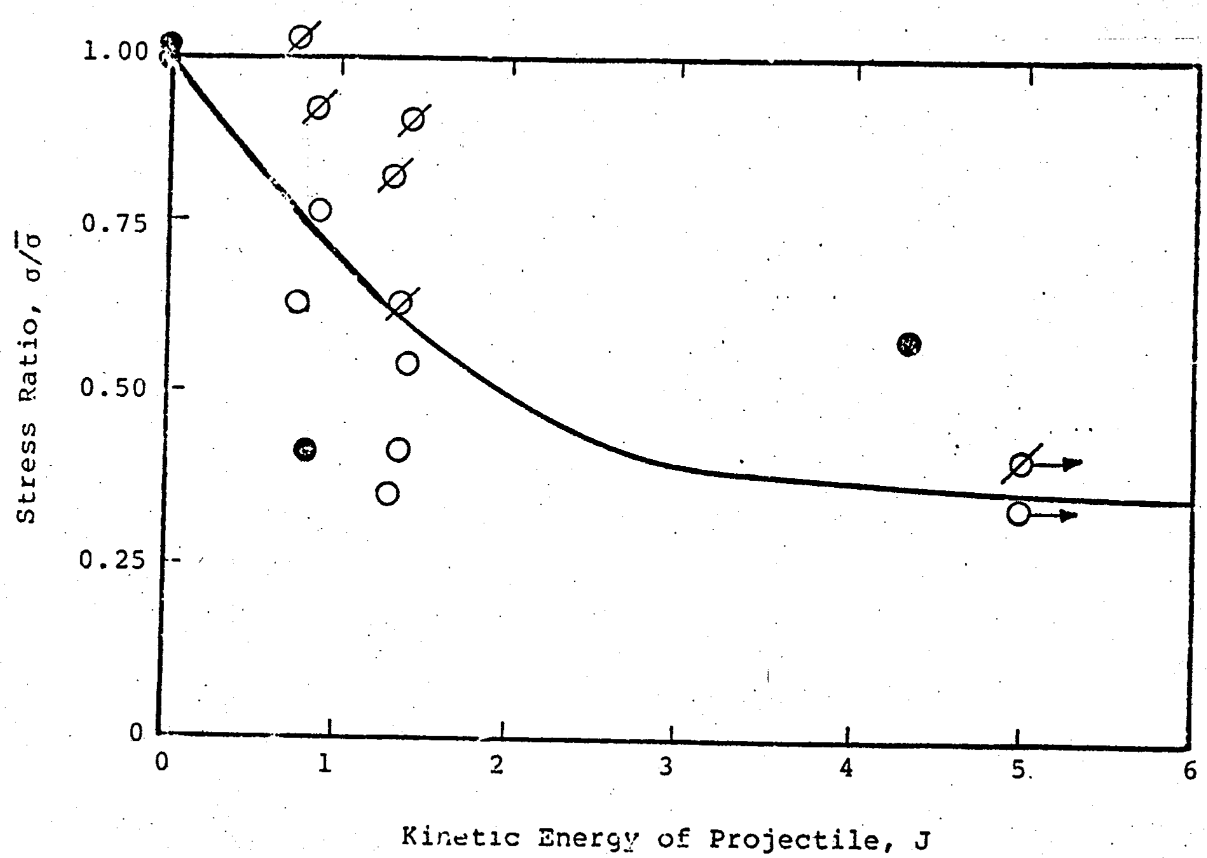


Figure 24. Normalized Stress vs. K.E of Projectile: B 20 Series

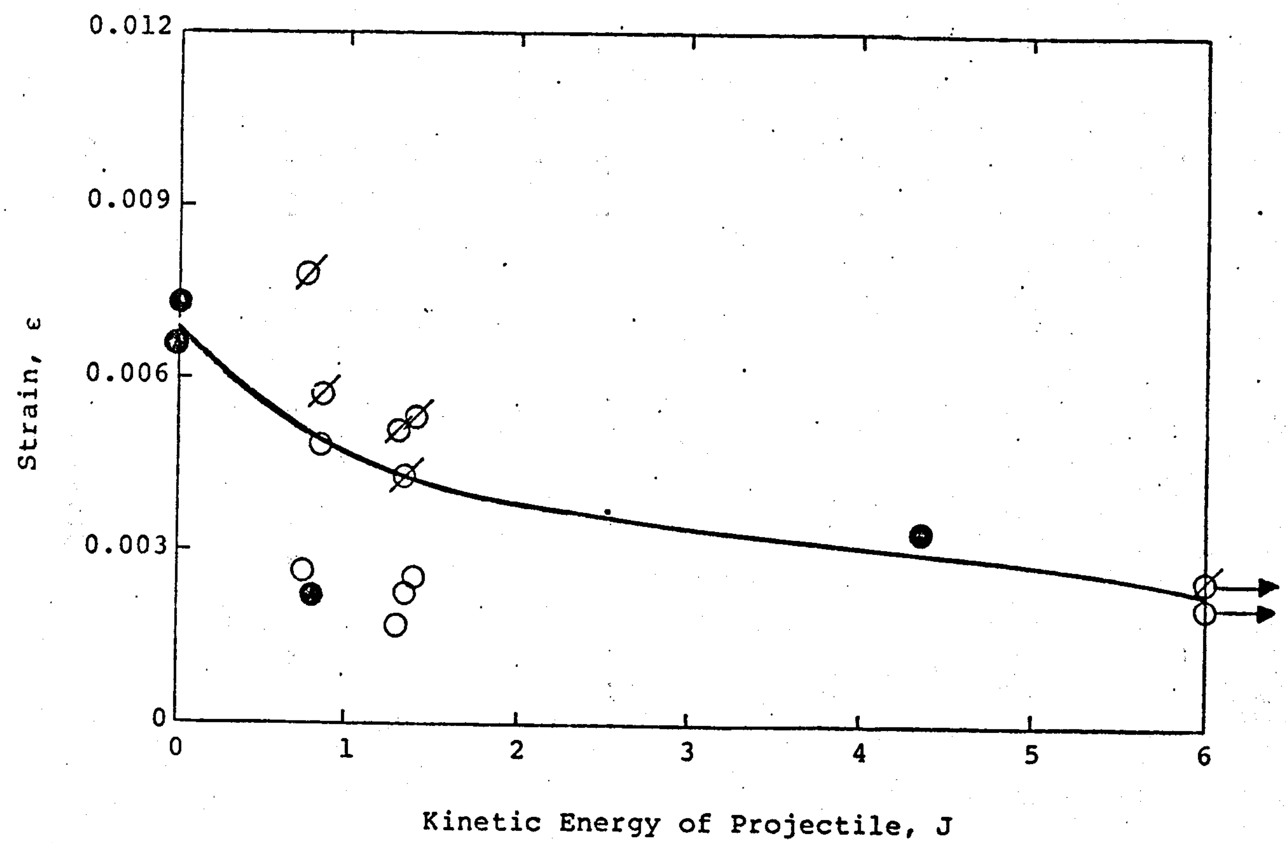


Figure 25. Strain vs. K.E of Projectile: B 20 Series

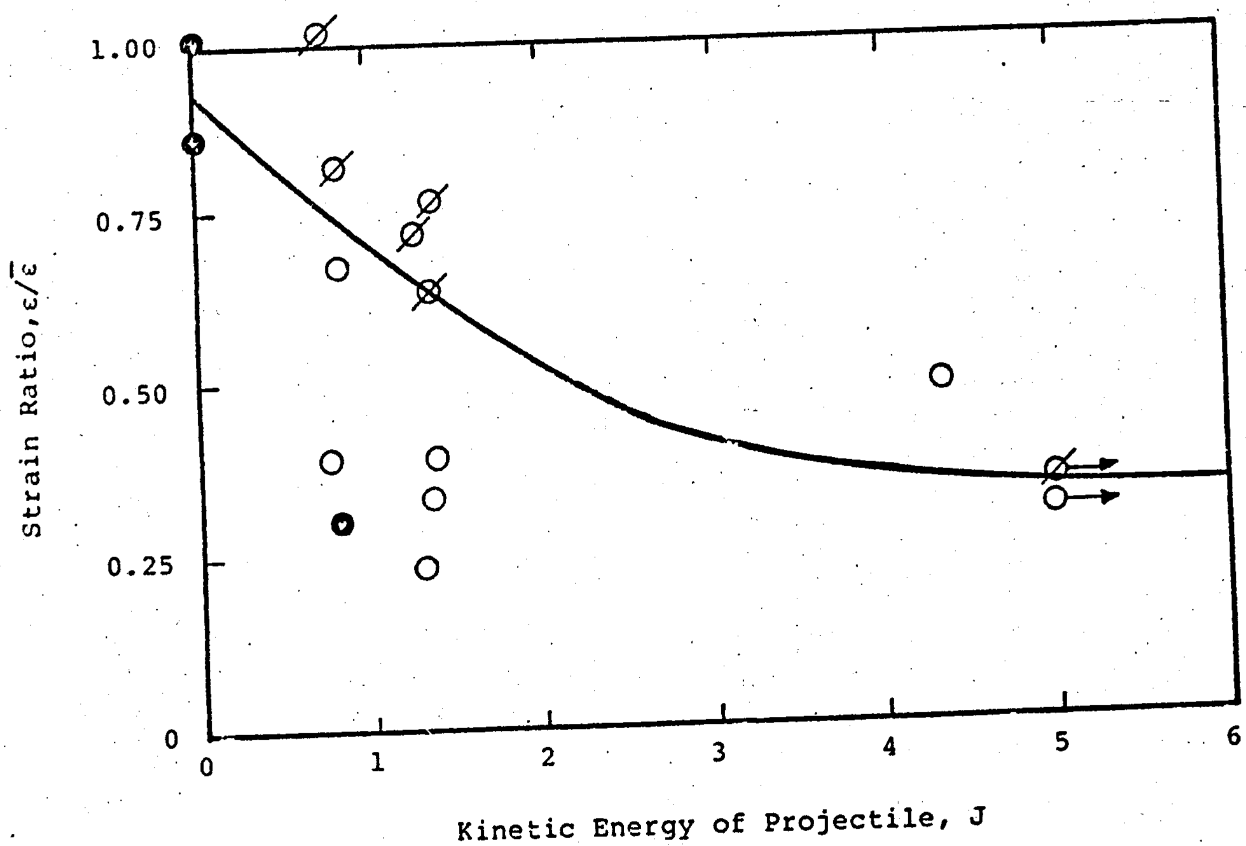


Figure 26. Normalized Strain vs. K.E of Projectile: B 20 Series

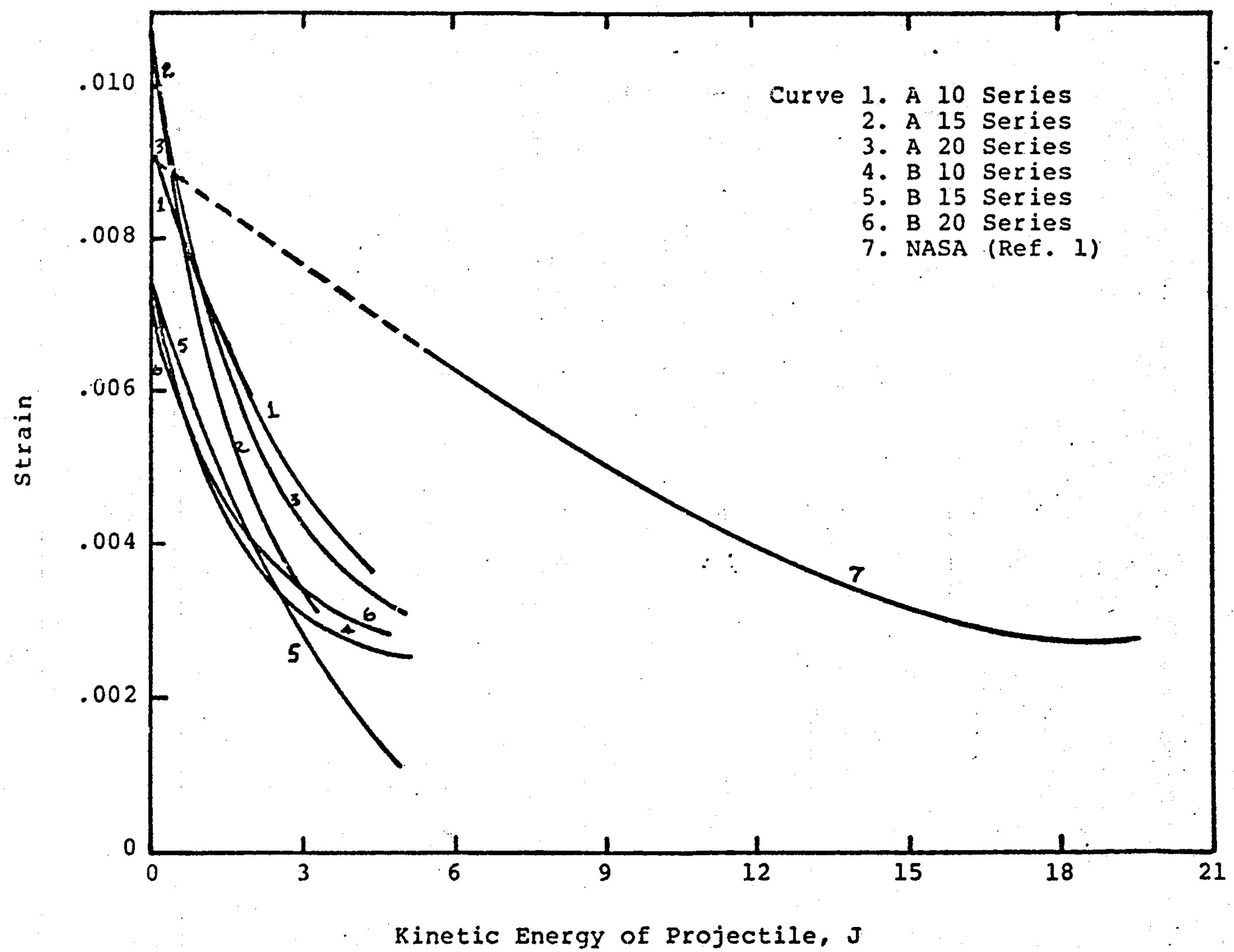


Figure 27. Strain vs. Projectile Energy (values taken from the faired threshold curves).

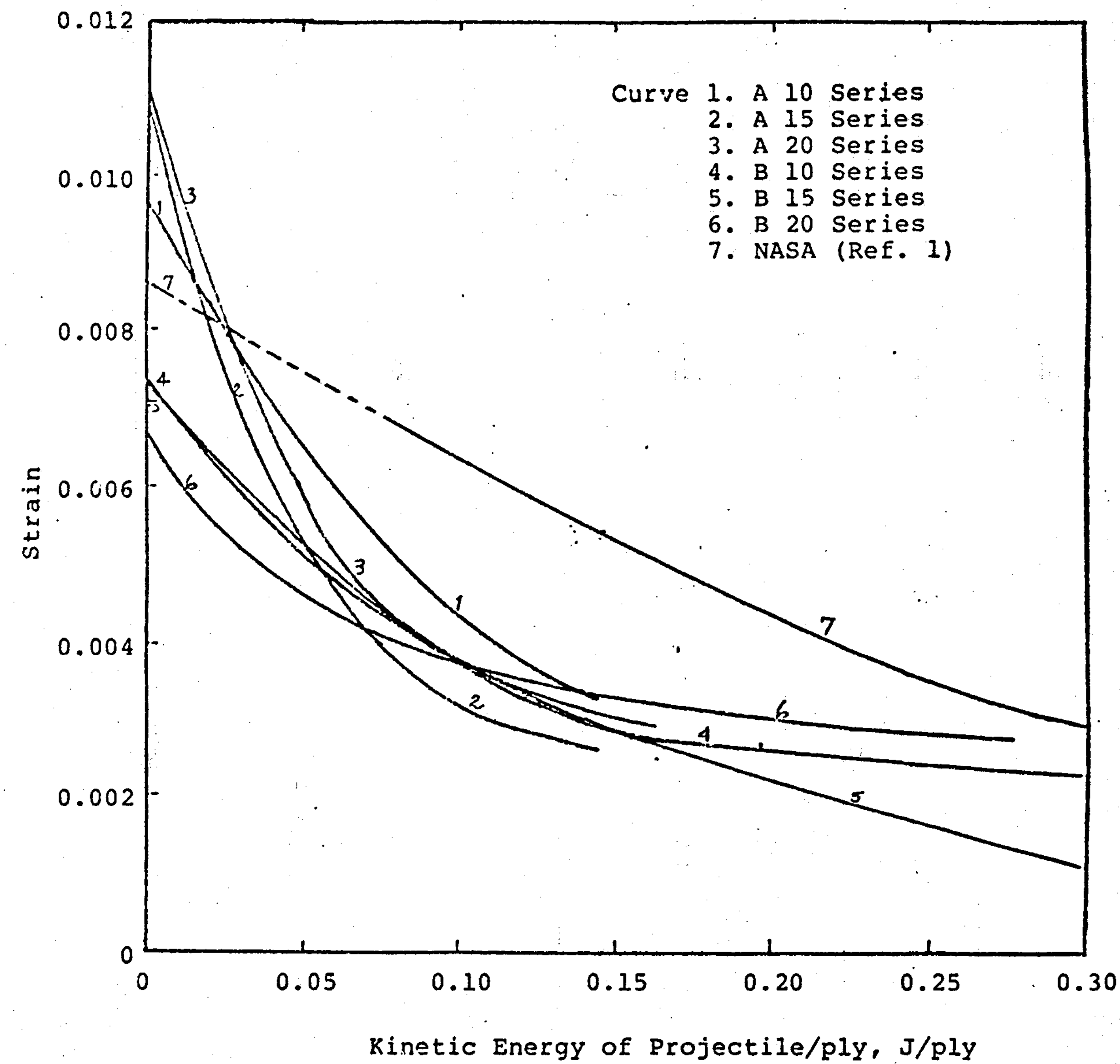


Figure 28. Strain vs. Projectile Energy/ply